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SOME METEOROLOGICAL RELATIONSHIPS IN THE PREDICTION OF TORNADOES

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ABSTRACT

Synoptic surface and upper air features are analyzed in relation to tornado occurrences. The findings are incorporated into a forecasting system by means of which a preliminary alert forecast of tornado areas can be issued in the early morning hours for the period 1100–2300 CST. Basically, the forecast is derived through the prognostic locations of favorable surface parameters relative to the cold axis at 200 mb. In a test of the system on independent data, most of the multiple outbreaks of tornadoes are correctly predicted.

1. INTRODUCTION

This paper presents the results of an investigation by a group of Eastern Air Lines' meteorologists under the direction of J. J. George. The objective is to help develop a system by means of which a preliminary alert forecast of tornado areas can be issued in the early morning for up to 24 hours from data time.

The study was confined to the occurrence or non-occurrence of tornadoes and their general location during the period 1100–2300 CST. The timing of tornadoes from a pre-dawn forecast deadline appeared to be nearly an insuperable problem at this time.

Information on tornado occurrences during the years 1950 through 1955 was supplied by the Severe Local Storm Center at Kansas City. These valuable data were the foundation for the project, permitting full use of the researchers' time on synoptic study. The months of January through June for the years 1950 through 1955 were utilized in the following fashion: 1950 through 1954 formed the period of the dependent data, while 1955 data were retained for an independent test.

The entire approach to the problem was from the viewpoint of the forecaster, using charts and data that are usually available in the forecast office. Theoretical considerations played a part in defining the strategy of the attack, but the forecasting techniques given are completely empirical and were, without exception, dictated by the data.

The advent of tornado forecasting is undoubtedly one of the most ambitious ventures into operational weather prediction since the inception of the science of meteorology. The climatological expectancy of tornadoes and the probability of precise forecast verification is indeed so low, that for years a "Hands Off" policy was deemed the only proper manner to treat this weather phenomenon. However, an apparent increase in tornado activity and public demand during the middle and late 1940's, led to a change in this professional policy, and the creation of the Weather Bureau's Severe Local Storm Center (SELS), which is charged with the responsibility of providing adequate warning of severe local storms to the general public.

Tornado forecasting, still in its infancy, must be approached in the strictest sense of short-range prediction. Therefore, at the present time, operational forecasts are directed toward the period of maximum occurrence; i. e., afternoon and evening, and are issued on a 1- to 6-hour warning basis. Currently involved in the SELS operation

[1] Project sponsored by U. S. Weather Bureau.

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is a forecast of a very general nature termed the "Convective Outlook." The convective outlook is issued by SELS at approximately 0500 CST, and in general terms outlines the forecast position which will likely be established in the form of a severe local storm warning later in the day. It is one of the purposes of this research to develop material which would include tornado activity in the convective outlook.

The tornado is one of the most complex and least understood mechanisms of meteorological phenomena, yet there is much we do know about the general meteorological environment in which these violent storms occur. For example, it is known that tornadoes occur in an airmass structure that is unstable. Since instability is an essential requirement for tornado activity, most of the current forecasting concepts involve a thermodynamic evaluation of hydrostatic instability based on predicted temperature and humidity values at various levels from the surface to 400 mb. A forecast of this nature is necessarily involved with the processes of horizontal advection, vertical motions, evaporation, and condensation. Therefore, forecasts of hydrostatic instability for periods in excess of 12 hours are subject to large error from a variety of sources.

Another commonly accepted qualitative conclusion is that most tornado outbreaks are favored in areas of warm, humid surface air near surface cyclones. In the presence of data which would support such a conclusion in a quantitative sense, one could draw the conclusion that an accurate prognosis of surface cyclones and surface moisture may well suffice as the initial vehicle with which to approach the longer-range forecast of airmass modification. The data in this research strongly suggest that the most powerful tool for the longer range severe weather forecast is an accurate prognostic surface chart relating to the placement and character of the surface cyclone and moisture pattern. This is indeed fortunate since, first, it represents an area of forecasting in which meteorologists are most experienced and therefore should be most proficient; second, it affords the use of a more compact data network allowing a better definition of parameters and patterns than procedures based principally on upper-air data. The intent of this discussion is not to deprecate the use of upper-air data in long-range tornado prediction. Indeed, an accurate prognosis of the surface patterns is dependent on the proper evaluation and prediction of dynamics involved in the lower and upper troposphere. However, the synoptic details relative to tornado occurrences are better defined and measured at the surface due to the frequency and density of the data.

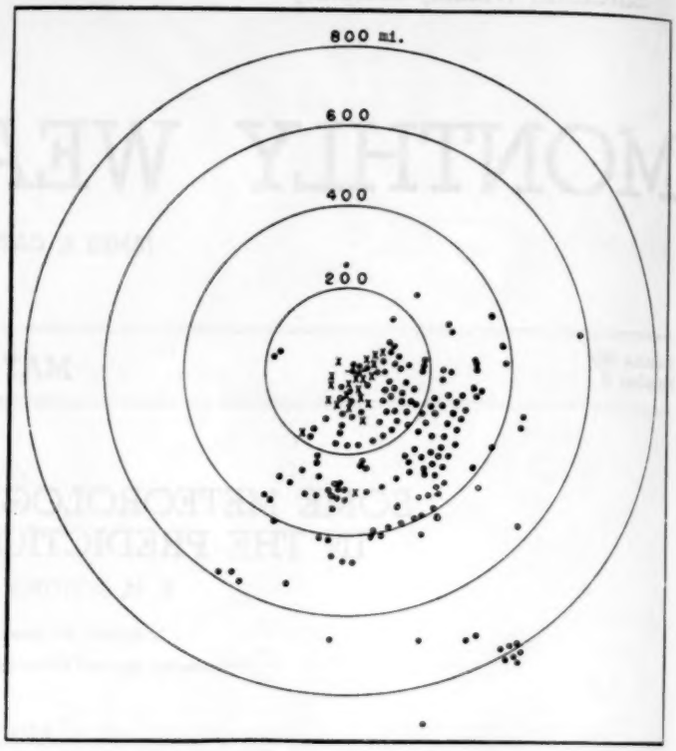

FIGURE 1.—Relationship of tornadoes to parent cyclone during January, February, and March, expressed in miles from cyclone center. North is at the top, east to right, etc. Circles are occurrences related to cyclones existing at 0030 CST. Crosses are occurrences related to cyclones which formed after 0030 CST; i. e., cyclogenesis.

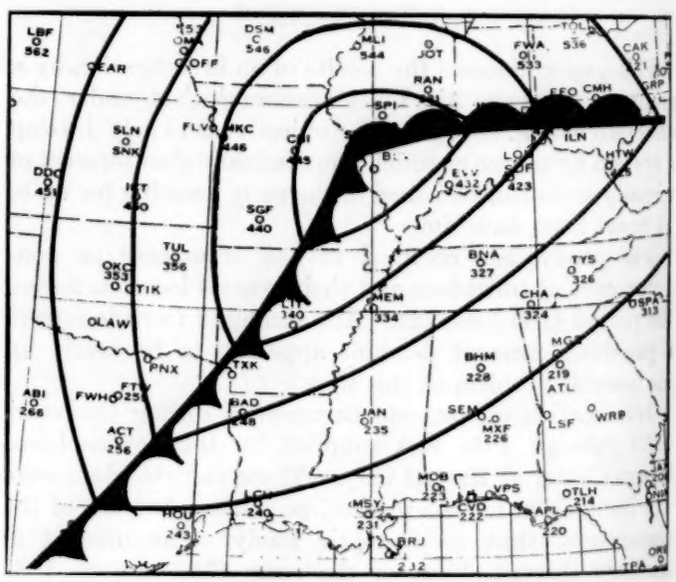

FIGURE 2.—A typical winter Low favorable for tornadoes in the southeastern quadrant.

2. SURFACE LOWS

Many researchers in the field of severe weather have noted that tornadoes occur in the southeastern quadrant of a wave cyclone, particularly if it is deepening. In attempting to define the validity of this qualitative conclusion, tornadoes over a 5-year period, 1950 through 1954, for the months January through June, were plotted by the month in relation to their parent cyclone at the time of occurrence. It was found that during January, February, and March, tornado activity was principally confined to the southeastern quadrant of the surface cyclone. However, beginning with April, a definite shift of tornado occurrences to the northeastern quadrant was

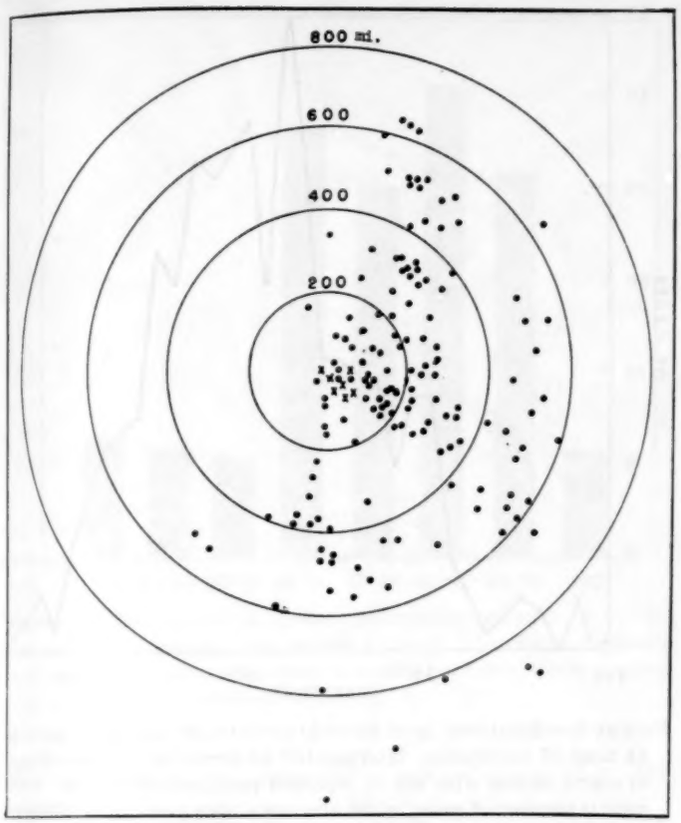

FIGURE 3.—Relationship of tornadoes to parent cyclone during April, expressed in miles from cyclone center. See figure 1 for explanation.

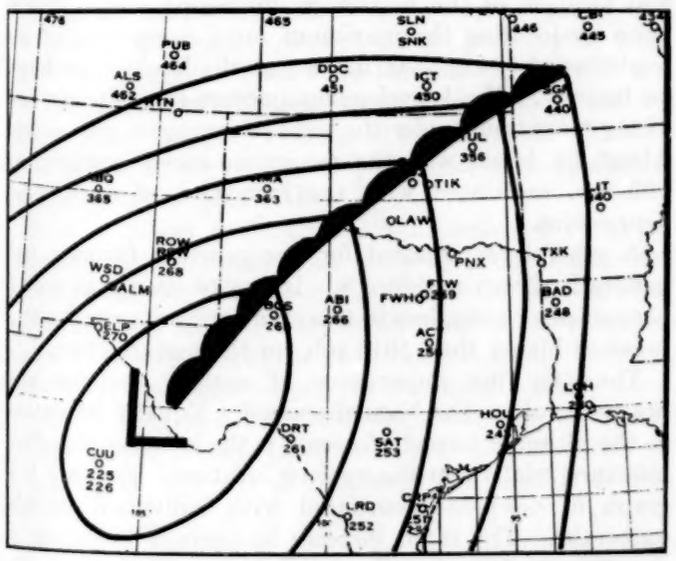

FIGURE 4.—A typical spring Low favorable for tornadoes in the northeastern quadrant.

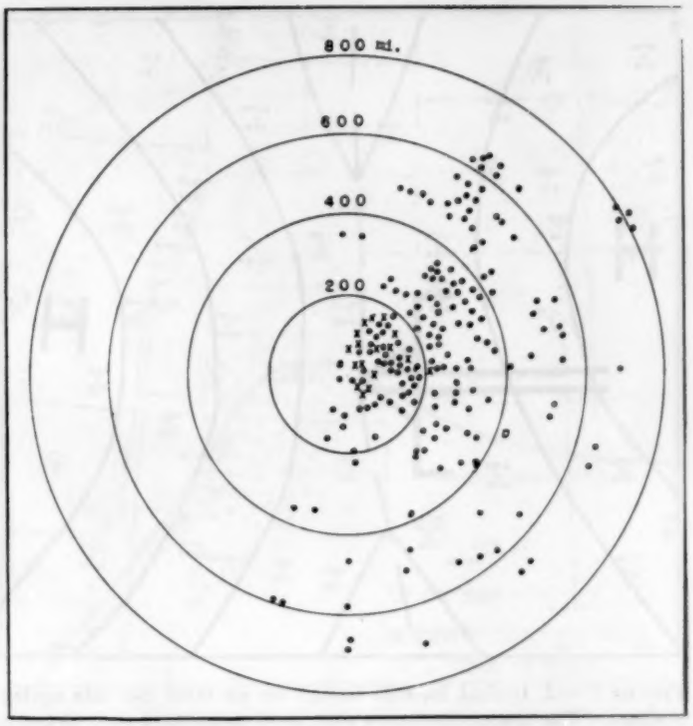

FIGURE 5.—Relationship of tornadoes to parent cyclone during May, expressed in miles from cyclone center. See figure 1 for explanation.

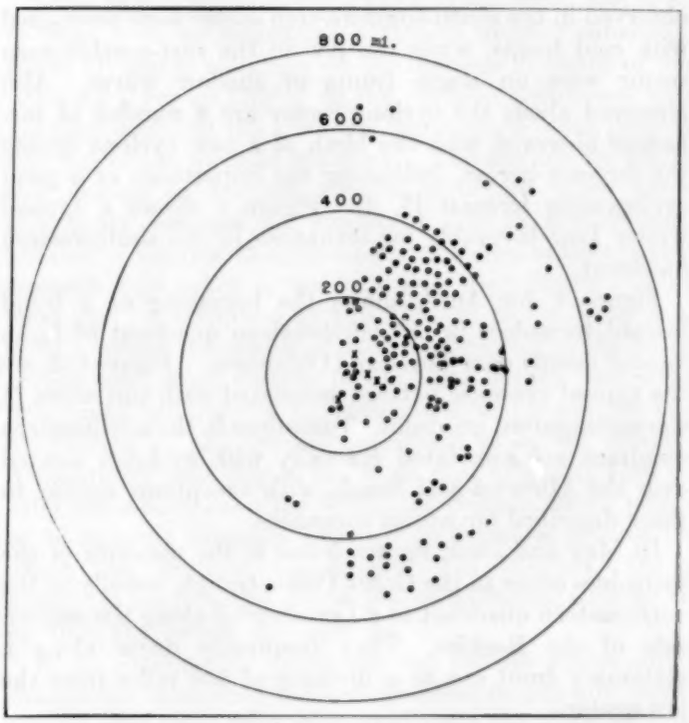

FIGURE 6.—Relationship of tornadoes to parent cyclone during June, expressed in miles from cyclone center. See figure 1 for explanation.

observed. In May and June, a positive maximum of tornadoes was found in the northeastern quadrant of surface cyclones.

Figure 1 is a plot of tornado occurrences relative to the surface cyclone for the months of January, February, and March. Most of the tornadoes are confined to a 450-mile radius in the southeastern quadrant. A significant group located about 700 to 800 miles south-southeast of the center was associated with very deep cyclones whose central pressures were less than 1000 mb. A few tornadoes

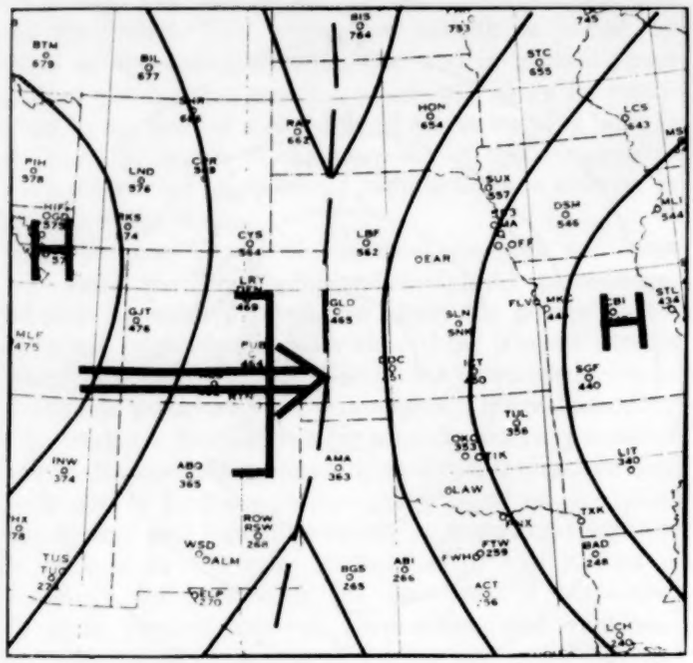

FIGURE 7.—A typical lee-side trough on an 0030 CST late spring chart. The bracket indicates west wind component over 25 knots at 500 mb., with the arrow through its mid-point indicating weak cyclogenesis expected in trough by 1830 CST.

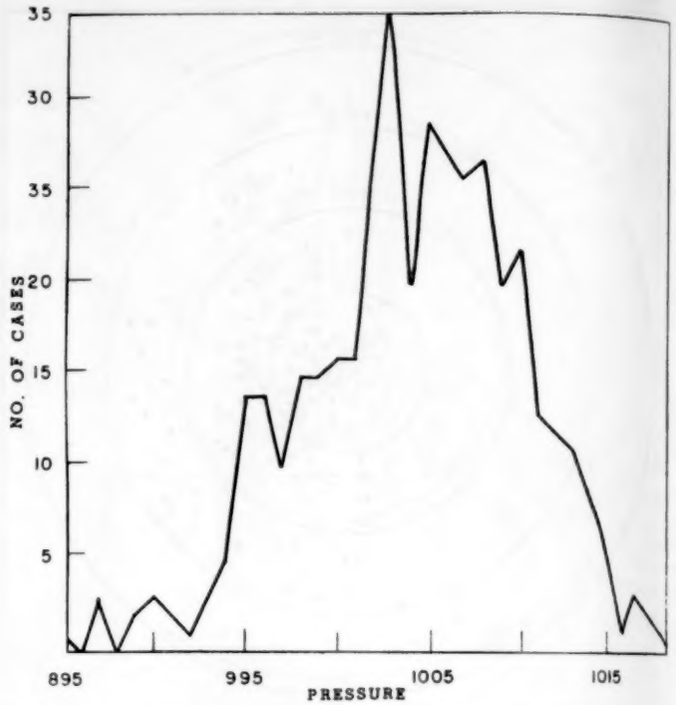

FIGURE 8.—Relationship of tornado occurrences to surface pressure at time of occurrence, interpolated to pressures between 6-hour synoptic charts with aid of reported pressure tendencies. Ordinate is number of cases, while abscissa shows pressure in millibars.

observed in the south-southwestern sector were associated with cold fronts, while the few in the east-northeastern sector were on warm fronts of shallow waves. Also clustered about the cyclone center are a number of tornadoes observed with the birth of a new cyclone during the forecast period, indicating the importance of a good cyclogenesis forecast [5, 6]. Figure 2 shows a typical winter Low favorable for tornadoes in the southwestern quadrant.

Figure 3, for April, shows the beginning of a trend toward tornadoes in the northeastern quadrant of Lows located mostly over Texas and Oklahoma. Figure 4 shows the typical synoptic pattern associated with tornadoes in the northeastern quadrant. Tornadoes in the southeastern quadrant are associated generally with cyclones located over the Midwest and South, with exceptions similar to those described for winter tornadoes.

In May and June, figures 5 and 6, the majority of the tornadoes occur in the Great Plains trough, usually in the northeastern quadrant of a Low located along the eastern side of the Rockies. They frequently occur along a stationary front out to a distance of 500 miles from the low center.

In the latter part of May and through June, a weak surface trough, often lying just east of the Rockies, is frequently the birthplace of weak cyclogenesis during the late afternoon. This presents a forecasting problem in that tornado areas are apparently linked to this particular development. A very simple method has been devised to predict and locate the area of such cyclogenesis. The leeward surface trough is, to a large extent, created by the mountain barrier effect combined with diurnal heating. Since diurnal heating is always involved, the only variable that needs to be considered is the degree and location of the maximum downslope area. This is done by locating the maximum zonal component of the westerlies at 500 and 700 mb. across the Rockies, as shown on figure 7. Weak cyclogenesis occurs immediately east of the mountains under the band of strongest west winds. About 25 knots was the minimum speed observed at 500 mb. associated with the formation of these weak depressions.

A general requirement for low pressure favoring tornadoes is shown in figure 8. It can be seen that only 5 percent of all tornadoes in this study were observed with a pressure higher than 1013 mb. on the surface chart.

Thus far the importance of surface cyclones and pressure values has been discussed. Equally important to the ultimate tornado forecast is the location of surface moisture relative to the cyclone location. Figure 9 is a graph of dewpoint associated with individual tornado outbreaks. The rapid increase in tornado frequency as the 60° F. dewpoint is approached suggests that this value may serve as a predictor. Figure 10 is a plot of tornado occurrences related to a typical 60° isodrosotherm. The cluster of activity near this line bears out the implications of figure 9.

An examination of the tornado cases in which the surface dewpoint was below 59° F. showed that they usually occurred within 250 miles of a low center of 1005 mb. or lower. The lower limit of the dewpoint in these cases was about 53°, although an occasional tornado was

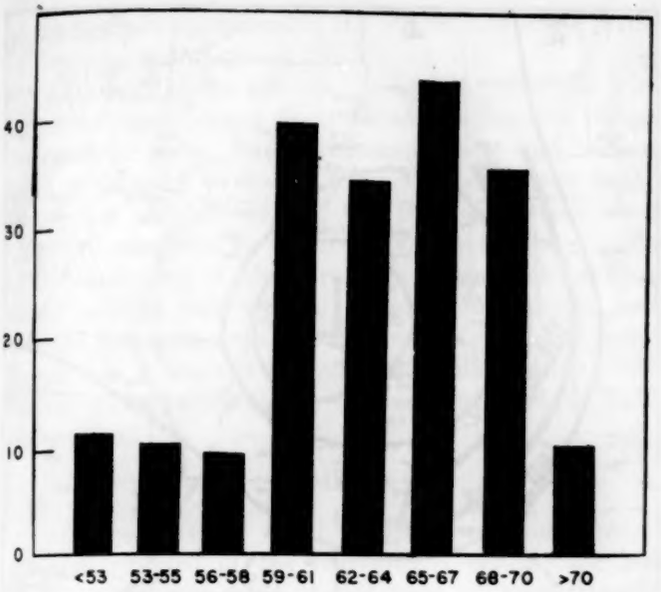

FIGURE 9.—Relationship of tornado occurrences to surface dewpoint at time of occurrence, interpolated between 6-hour surface charts whenever necessary. Ordinate is number of cases, while abscissa shows surface dewpoints in degrees F.

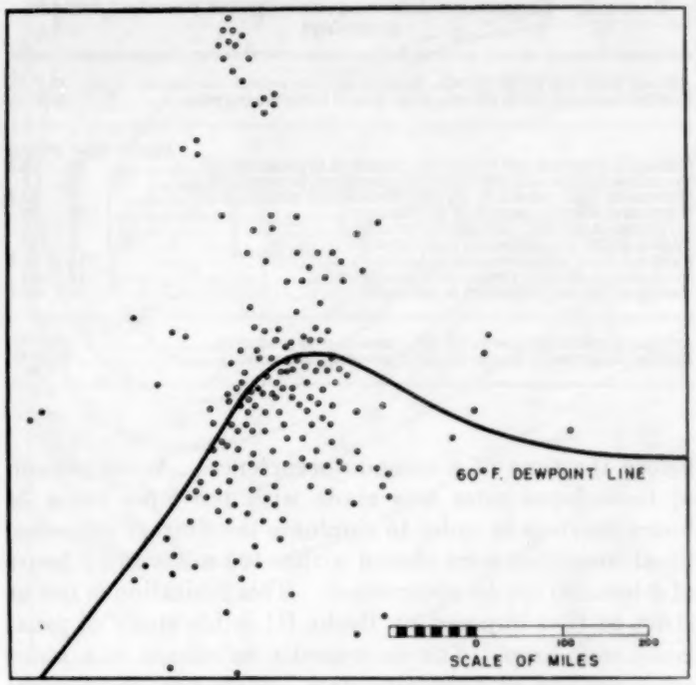

FIGURE 10.—Relationship of tornado occurrences to the surface 60° F. isodrosotherm during the months of January, February, and March.

observed near a deep low center with dewpoints in the upper forties.

The foregoing discussion emphasizes the importance of predicting the movement of surface moisture patterns. The displacement of surface moisture was found to be along the surface geostrophic wind and inversely proportional to the dewpoint gradient over a trajectory indicated by full advection of dewpoints with the geostrophic wind. Only two dewpoint lines were considered, the 53° and 60° isodrosotherms. All forecasts were made from the 0030 CST map and projected for 12 and 18 hours. Table 1 gives the percentage of geostrophic wind to be applied to various dewpoint gradients.

When a warm front crosses the predicted dewpoint trajectory, it was found that the projection of the dewpoint lines should be made in 6-hour increments. In most cases the warm sector is sufficiently moist to allow projection with 100 percent of the geostrophic wind to the warm front, then slowing abruptly to the speed of the warm front. In May and June, sufficient moisture is usually present ahead of the Low, even into the northeastern quadrant, so that the prognosis of dewpoint is seldom necessary.

3. STABILITY CONSIDERATIONS

The examination of thermodynamic diagrams has always seemed the most likely starting point for tornado forecasting, because of the extreme instability demonstrated by tornadoes and accompanying phenomena. Throughout the earlier stages of tornado research, a concept of a typical airmass structure involving a low-level inversion capping a moist layer surmounted with dry air, was considered a requirement for tornado outbreaks.

More recent investigations have raised some doubt as to what is to be considered a typical tornado sounding. Beebe [1] places emphasis on the increase in depth of the moisture layer just prior to the tornado occurrence and the destruction of the low-level inversion so often present well before the tornado outbreak. The method by which this change in vertical airmass structure takes place necessarily assumes an important role in the tornado forecast. Many soundings which were used in the original research were taken in the southern Great Plains area at 0900 CST. A sounding at this time of day reflects to a certain extent the results of nocturnal cooling in the lower atmosphere, since surface heating has not by this time progressed sufficiently to contribute materially to the destruction of the inversion through turbulent mixing. A proximity sounding in the same area taken at 1500 or 2100 CST would have the benefit of full insolation which could in some instances explain the principal process by which the airmass modification was effected. Other soundings may require a dynamic or advective element to produce the proper modification.

In an attempt to determine the factors which could change the lapse rate through the 850- to 500-mb. layer, several soundings were evaluated near the site and just

TABLE 1.—*Percent of geostrophic wind to be applied to various dewpoint gradients to project isodrosotherms*

Dewpoint gradient (from starting point to terminal point using 100 percent of geostrophic flow)	Percent of geostrophic wind
1 to 10 degrees	100
11 to 16 degrees	70
over 16 degrees	50

TABLE 2.—*Comparison between proximity and precedent tornado soundings*

Average lapse rate 850 to 500 mb., 24 hours prior to tornado occurrence	25.5° C.	
Average lapse rate 850 to 500 mb., near time of tornado occurrence	28.0° C.	
	Number cases	*Percent*
Increase in lapse rate 850 to 500 mb.; precedent to proximity	29	72.5
No change in lapse rate 850 to 500 mb.; precedent to proximity	2	5
Decrease in lapse rate 850 to 500 mb.; precedent to proximity	9	22.5
Warming at 850 mb.; precedent to proximity	28	70
No change at 850 mb.; precedent to proximity	6	15
Cooling at 850 mb.; precedent to proximity	6	15
Warming at 500 mb.; precedent to proximity	15	37.5
No change at 500 mb.; precedent to proximity	14	35
Cooling at 500 mb.; precedent to proximity	11	27.5
Average temperature change 850 mb.; precedent to proximity	+2.7° C.	
Average temperature change 500 mb.; precedent to proximity	+0.2° C.	

before the time of a tornado occurrence. A comparison of these lapse rates was made with the lapse rates 24 hours previous in order to eliminate the diurnal influence. Final soundings were chosen within 100 miles and 2 hours of a tornado for 40 occurrences. This limitation is not as strict as that imposed by Beebe [1] in his study of proximity soundings. The data used here cannot in a strict sense qualify as proximity data. However, the general trend of warming or cooling at different levels should be significantly portrayed by the method. For the sake of convenience, the older data will be referred to as precedent data, and the data near the time and place of tornado occurrence as proximity data. Table 2 lists the pertinent comparisons between the proximity and precedent data studied in this report.

It is noted that in a number of cases the lapse rate between 850 and 500 mb. actually decreased just before the tornado outbreak. This can possibly be accounted for by the development of general cumulus activity and airmass saturation which would establish a moist adiabatic lapse rate over the area in question. Warming occurred at 850 mb. in more than 70 percent of the cases, with a few cases preceded by cooling. This cooling may be accounted for by vertical motion, evaporation, or advection. At 500 mb. there appears to be no significant trend, with the data evenly distributed among warming, cooling, and no change.

The general inference of this table suggests warming in the lower levels as the apparent cause of the increase in the lapse rate for the majority of cases.

4. 850-MB. LEVEL

From the surface data presented, it is apparent that an accurate forecast of the surface cyclone is essential to a successful tornado forecast. Equally important is the prognosis of deepening, filling, and cyclogenesis.

George [5] has demonstrated that an area of strong cold advection in the lower troposphere could be utilized as a predictor of cyclogenesis and deepening. This synoptic feature is best obtained at the 850-mb. level, although it is sometimes necessary to inspect the 700-mb. level when the 850-mb. trough is situated close to the Rocky Mountain chain. This parameter has been designated by George as a "Cold Injection", and is illustrated in figures 11 and 12.

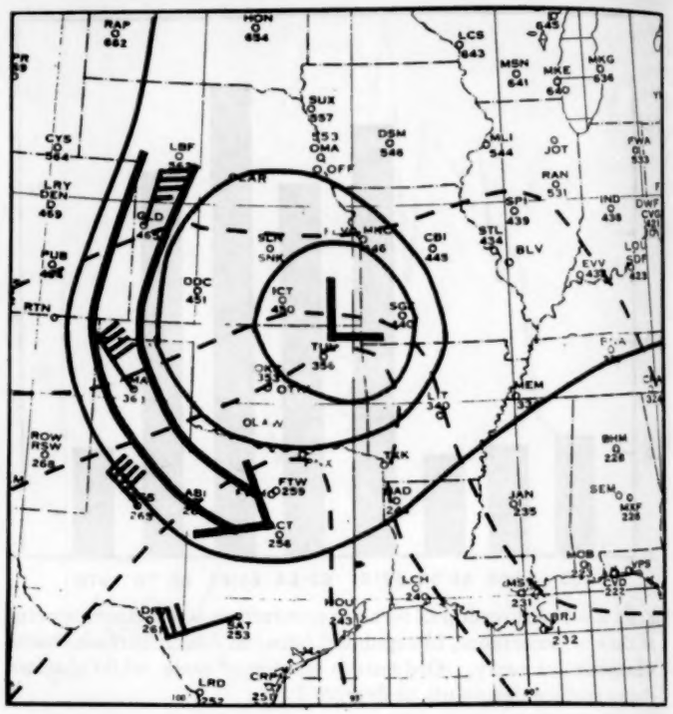

FIGURE 11.—A typical cold injection at the 850-mb. level (Dec. 5, 1954, 0300 GMT) prior to an outbreak of tornadoes in Alabama and Georgia. Dashed lines are 5° C. isotherms.

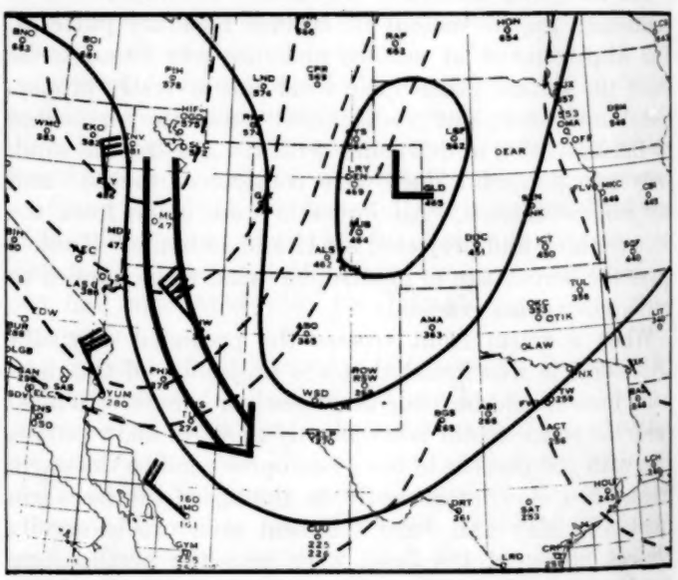

FIGURE 12.—A portion of the 700-mb. chart for February 19, 1954, 0300 GMT shows that a strong cold injection at 700-mb. level over the higher terrain of the Mountain States will often be as effective as an 850-mb. cold injection in the indication of a tornado day. In this illustration, numerous tornadoes were reported in Oklahoma the following afternoon.

The cold injection is *not* introduced as a prerequisite of tornadoes, but rather as a forecast tool in the preparation of the surface prognostic chart. It is significant to note, however, that the cold injection was present in 77 percent

of the tornado situations in the winter and in 64 percent of the cases in the spring.

To the east of the 850-mb. trough, the observed winds usually display strong south wind components, usually 25 knots or more, forcing a temperature and moisture ridge northward over the tornado site by the time of occurrence. Unfortunately, this feature is often absent 18 to 24 hours prior to occurrence of the tornadoes. Due to the up-welling of moisture from lower levels, evaporational cooling, and vertical motions, satisfactory prognosis of the temperature and moisture ridge for periods longer than 6 hours is extremely difficult. Much greater success was attained if this forecast was confined to the surface data.

5. 500-MB. LEVEL

Since the 500-mb. chart is the most complete and quickly available of the higher-level charts, the most intense study was made at this level. The outstanding features of this level near tornado time were taken from composite charts, after Beebe [2]:

1. The presence of a large trough west of the tornado area.
2. Winds averaging 50 knots over and to the north of the tornado area.
3. Practically no thermal advection.

A series of composite charts drawn from the charts available at forecast time (2100 CST in most cases) for several early season multiple tornado outbreaks showed some distinct features:

1. An isotherm ridge over the future tornado zone.
2. A difluent contour pattern from the trough to the eastern ridge.
3. A definite jet maximum in the trough west or southwest of the forecast tornadoes.
4. A −15° C. isotherm through the tornado area.

It was found that composite charts obscured such a variety of individual 500-mb. patterns that they became nearly useless as tornado predictors. For example, winds as low as 25 knots, temperature ranging from −5° to −22° C., and completely straight flow more than 1,000 miles west or southwest of the tornadoes were observed. Some cases showed nearly parallel flow from 850 to 500 mb.

Individual predictors at this level were analyzed in detail, and although each one added confidence to the tornado forecast, no single one, nor combinations of two or three seemed to hold up for more than one season:

(1) The isotherm ridge east of the trough during the years of 1953 and 1954 forecast the longitude of the tornadoes within 3° about 84 percent of the time, but failed in other years when many cases of straight contours and isotherms at 500 mb. accompanied tornadoes.

(2) The deepening or filling of a trough from forecast time to tornado time invalidated an attempt to fix the latitude of the tornado by the latitude of the isotach maximum and the vorticity maximum in the trough.

(3) Because tornadoes frequently occur along certain isotherms, they were averaged and tabulated by months, as shown in table 3, but again natural variability was so great as to render this useless as a forecasting parameter.

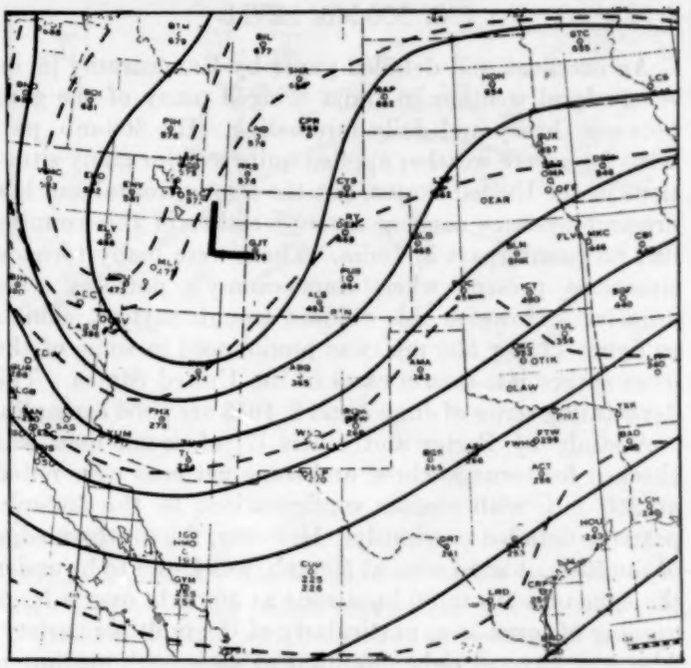

FIGURE 13.—A typical 500-mb. chart (Feb. 19, 1953, 0300 GMT) preceding tornado outbreaks over the Great Plains during the following afternoon. The isotherm ridge over the Plains, as in this case, was often a good predictor of the longitude of the expected tornadoes.

(4) Fast-moving shallow troughs were quite accurate predictors, when available. The tornadoes occurred about 350 to 400 miles ahead of the trough line with favorable surface conditions present, and about due east of the isotach maximum in the trough.

(5) The forecast position (at times difficult) of the southern edge of the 50-knot wind stream at 500 mb. over a favorable surface area was often helpful for latitude determination of tornadoes.

(6) Cold Lows at 500 mb. moving east from the southern Rockies [4] were often producers of extensive severe weather and multiple tornado situations.

(7) The rather surprising frequency of tornadoes under straight flow at 500 mb. made all of the previous 6 forecasting aids unusable during these conditions. The only help in these cases seemed to be the intersection of a 50-knot wind zone with favorable 850-mb. and surface predictors.

TABLE 3.—*The average isotherm at 500 mb. over future tornado location*

Month	Average Isotherm (° C.)
January	−15
February	−15
March	−14
April	−13
May	−11.5
June	−9.5

6. 300-MB. LEVEL

An excellent and detailed paper by Ramaswamy [8] on severe local weather in India bridged many of the gaps between theory and daily forecasting. His 300-mb. patterns for severe weather applied quite well for many situations in the United States, but the strong frontal and low pressure systems causing severe weather in this country had no counterpart in India. There were many tornado situations present when Ramaswamy's patterns were negative. However, his difluent trough pattern, similar to figure 13, for 500 mb. was pronounced in some of the most severe late-season cases in the United States. The devastating series of June 7 and 8, 1953 are good examples.

A study by Porter and others [7] of squall lines was checked for tornado clues, and some patterns were noted at 300 mb. with similar configurations to the 500-mb. patterns detailed previously. However, the southern edge of the 50-knot wind zone at 500 mb. was found to be under the edge of a 70- to 80-knot zone at 300 mb. over a large number of tornadoes, particularly of the multiple variety. Also, the forward right quadrant of an isotach maximum in the main jet stream was a favorable location, although this finding was not usable when projected for an 18-hour forecast.

7. 200-MB. LEVEL

A feature of the 200-mb. level which consistently located the site of subsequent tornado outbreaks was the axis of the cold tongue. This relationship was noted during the study of the developmental data when the cold tongue was related to tornado areas. During the test year of 1955, individual tornadoes occurring between the hours of 1100 and 2300 CST were plotted relative to the axis of the 200-mb. cold tongue as delineated by the 2100 CST data of the previous evening. This distance from the tornado site to the cold axis was measured in degrees of latitude and the results are tabulated in table 4.

From this table it is noted that 74 percent of the tornadoes occurred within 2° of latitude of the cold axis. It is emphasized that this is not a synoptic measurement, as the tornadoes occurred 14 to 26 hours after the time of the data used to define this parameter. No specific values seemed to be required, although in the majority of the cases the temperature along the cold axis was −60° C. or colder. This figure agrees closely with the findings of Galway and Lee [3] of the SELS Center. They related tornado occurrence to a jet intersection at 200 mb. with the southwestern quadrant of the cold pool as outlined by the −60° C. isotherm. They describe this pattern as a simultaneous relationship to the tornado occurrence. In this research, however, the axis of the cold tongue is presented as a predictor valid for time periods up to 26 hours from data time.

TABLE 4.—*Frequency of distances of tornado sites from 200-mb. cold tongue of previous evening*

	Tornado distance from cold axis (° lat.)				
	0	1	2	3	Over 3
Number of cases	100	74	62	37	47
Percent of cases	31	23	20	11	15

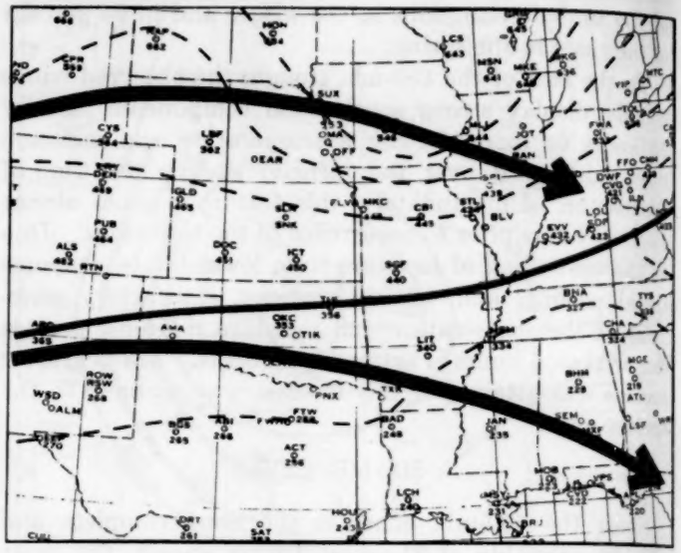

FIGURE 14.—An illustration of the axis of a cold pool at 200 mb. lying between two jet streams. Thin solid line is axis of cold tongue while heavy lines show jet streams. Thin dashed lines are isotherms at 2° C. intervals.

8. FORMULATION OF THE FORECAST

Basically the forecast is derived through the location of favorable surface parameters relative to the cold axis at 200 mb. From a forecasting standpoint this requires a surface prognostic chart for locating the low center and moisture pattern expected 12, 18, and 24 hours after the 0030 CST surface map available at forecast time, along with the 200-mb. cold axis delineated by isotherms drawn for 2° intervals at 2100 CST of the previous evening. Often there is a cold axis parallel to, and between, two jet streams as in figure 14. At times, however, branches of the cold axis appear, and these should be considered also, as in figure 15.

The forecast can be made in the following steps during January, February, and March (see fig. 16):

1. Prognosticate position of surface cyclone and fronts for 1230, 1830, and 0030 CST.
2. Prognosticate 60° F. dewpoint lines for each prognostic chart.
3. From prognostic low center draw a 450-mile radius from cold front to warm front through warm sector.
4. Outline 60° F. dewpoint area within above radius.
5. Eliminate prognostic pressure areas expected to be above 1013 mb. within above radius.
6. Plot 200-mb. cold axis on surface prognostic charts.
7. Designate alert area as that portion of favorable surface area intersected by 200-mb. cold axis, including a 2° latitude strip on either side of the axis within the surface area.

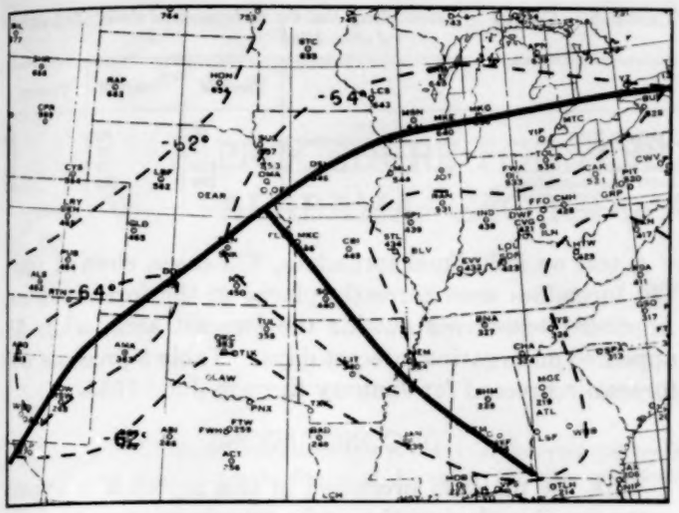

FIGURE 15.—An illustration of the axis of a cold pool at 200 mb. with a branch extending into the Gulf States.

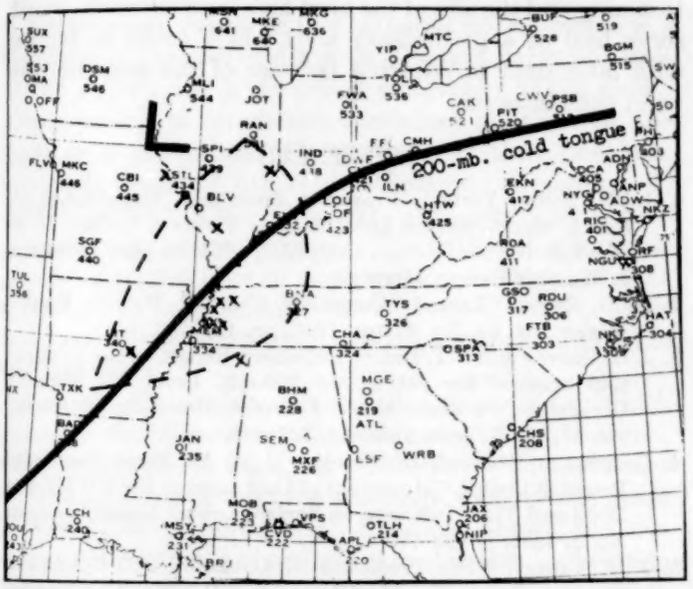

FIGURE 16.—A typical tornado alert area for a winter month, outlined by the dashed line. The area is bounded on the west by the prognostic position of the cold front for 1830 CST, on the south by a 450-mile radius from the prognostic low center, and on the northeast by the prognostic 60° F. isodrosotherm. The 200-mb. cold axis is the actual position from the 2100 CST chart of the previous evening. Tornado occurrences are located with small crosses.

8. Exceptions to steps 2 and 4: If the low center pressure is less than 1005 mb., the dewpoint is in the 53° to 59° F. range, *and* a 60° F. dewpoint is within 450 miles of the low center, a favorable surface area lies in the warm sector within a 250-mile radius of the low center.

The favorable surface area indicated on the 1230 CST prognostic chart may come under the 200-mb. cold axis, and an alert should begin at 1230 CST. However, if the favorable surface area does not reach a 200-mb. cold axis until 1830 CST, the alert should be delayed until that time.

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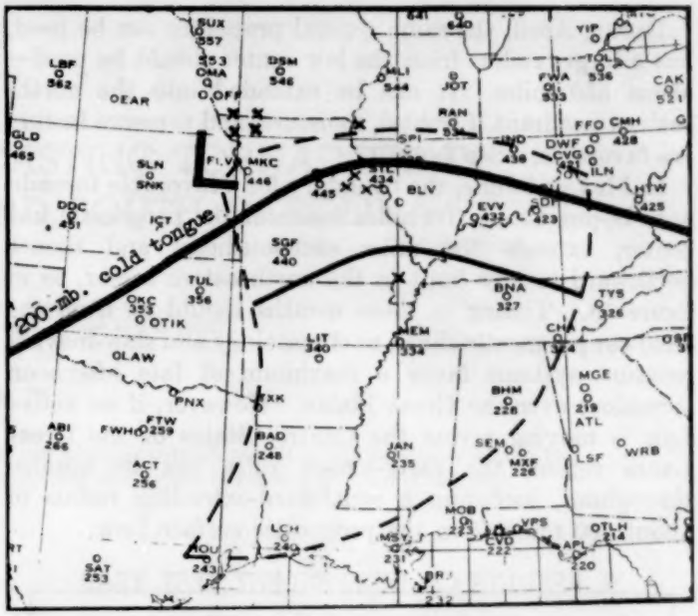

FIGURE 17.—A typical tornado alert area for April, outlined by the dashed line. The area is bounded on the west by the prognostic position of the cold front for 1830 CST, on the south by a line 2° of latitude from the 200-mb. cold axis, on the east by a 550-mile radius from prognostic low center, and on the north by the prognostic position of a warm front. Tornadoes are indicated with small crosses.

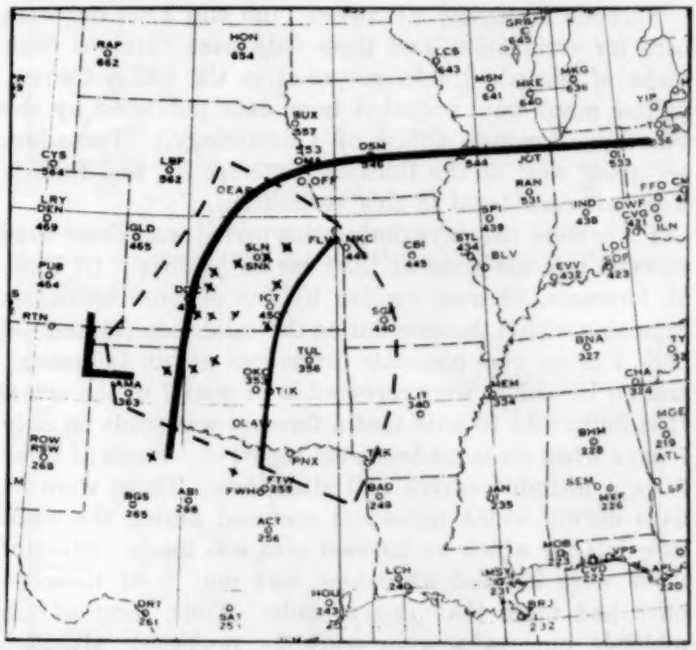

FIGURE 18.—A typical tornado alert area for a weak or moderate Low in May and June, outlined by the dashed line. The area is bounded on the west and northwest by prognostic frontal positions, on the northeast and south by distance limitations (see text) from prognostic low center, and on the east by a line 2° of latitude from the 200-mb. cold axis. Tornadoes are indicated with small crosses.

The forecaster's judgement should be used for appropriate timing by these considerations during the entire period from 1230 until 0030 CST.

During April, the same general procedure can be used, but a larger radius from the low center should be used—about 550 miles. It can be extended into the northeastern quadrant if frontal, moisture, and pressure factors are favorable. See figure 17.

In May and June, the boundary for a favorable tornado area begins about 100 miles south of the prognostic low center, extends 500 miles east-southeast and thence northward to any front in the northeastern sector, as in figure 18. Timing in these months should be from the 1830 CST prognostic chart, as climatology and slow-moving pressure systems favor a maximum of late afternoon tornadoes over the Great Plains. However, if an active Low is moving across the Central States or the Great Lakes region, the early-season rules can be applied throughout, including a southward-extending radius of about 500 miles from the prognostic surface Low.

9. RESULTS OF INDEPENDENT TEST YEAR

A forecast was made for each day of the test period, January through June 1955. These test forecasts were based upon 0030 CST surface maps plus the 2100 CST 200-mb. charts, and were valid for 1830 CST. An alert area was outlined if *all* of the conditions specified in section 8 were met. Obviously, if they were not met, no area was outlined and the test forecast was for no tornadoes.

Tornado occurrences between 1100 and 2300 CST were used for verification, and these data were obtained from maps of tornado tracks prepared in the SELS Center. (These maps were prepared from data published by the Weather Bureau's Office of Climatology.) Tornadoes occurring west of the Rockies, waterspouts, and funnels were not considered in this verification.

There were 181 days during this period, and there were tornado forecast areas at 1830 CST on 55 days. Of these 55 forecasts, 39 were verified by one of more tornadoes occurring within the area during the valid time (1100–2300 CST), 9 areas were near-hits (tornadoes within 140 miles), and no tornadoes were reported in or near 7 of the areas. It is important to note that a forecast was made on only 7 days when no tornadoes were reported. Some of these 7 days included severe hail situations. There were 34 days during which tornadoes occurred during the valid time but for which no forecast area was made. Most of these were isolated tornadoes, and only 6 of these 34 days had more than one tornado. Thus, most of the multiple outbreaks were correctly predicted, although there may have been some error in location because of slight errors in the surface prognostic chart.

TABLE 5.—*Results of forecasting test on independent data, January-June, 1955*

	Forecast	Observed	Percent
Tornado days	48	82	59
Tornado areas	55	39	71
No tornado days	126	99	79
Individual tornadoes	180	335	54

A test on individual tornadoes, 335 cases, showed that 180 tornadoes were correctly placed in the forecast area. Another 60 occurred outside the forecast area, while 95 appeared on negative forecast days. Table 5 presents the forecasting record for January through June 1955.

10. CONCLUSIONS

With the material presented in this report it is apparently possible during the early morning hours to issue successful forecasts of afternoon and evening tornadoes. The forecasts, however, are quite general in nature relative to timing and the size of the alert area, and therefore would serve best as a preliminary alert which could be refined with later data in reducing the size of the area and the valid time interval.

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A PROCEDURE FOR FORECASTING TORNADOES IN ALABAMA, GEORGIA, AND SOUTH CAROLINA

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ABSTRACT

An effective procedure is devised for determining by 0400 EST whether tornadoes will or will not occur within the area comprising the States of Alabama, Georgia, and South Carolina during the remaining portion of the day.

1. INTRODUCTION

A categorical answer as to whether or not a tornado will occur within the area of Alabama, Georgia, or South Carolina on a given day is the primary objective of this study. The approach to forecasting tornadoes in this area was made in a somewhat different manner than has been previously used by other investigators. Armstrong [1] used primarily the 700-mb. chart, while others [3, 4] used primarily upper-air soundings. The data used were those next prior to the time of occurrence. In this study the approach has been through the analysis of several levels which contribute to instability of the atmosphere over the tri-State area.

A check of available studies failed to show one which restricted the climatology of tornadoes to only Alabama, Georgia, and South Carolina. Therefore a survey of the tornado statistics of this area was made, to serve as a guide to forecasting requirements. Figure 1 shows the frequency of occurrence of tornadoes in this area by hours to the nearest hour of the day, during the years 1950 through 1955. (Eastern Standard Time is used throughout this study.) Data for years prior to 1950 were not used because it did not seem likely that they would include all tornadoes which had occurred. Figure 1 shows the preponderance of occurrences in the late afternoon over early morning hours. The peak at 1800 EST is twice that of a secondary peak at 0800 EST. The minimum between 2300 and 0300 EST indicated this is the period for which forecast coverage is least needed; therefore, a calendar day forecast is made using the 0130 EST surface map and 2200 EST upper-air data. By 0400 EST a forecast for the date in question can be made. Since only 4 percent of the tornadoes occur before 0400 EST, the few missed before this time are negligible in considering a forecast to be issued only once a day for an affirmative or negative answer on tornado occurrence during the rest of the day. No study has been made of the timing, although some observations on this will be made later.

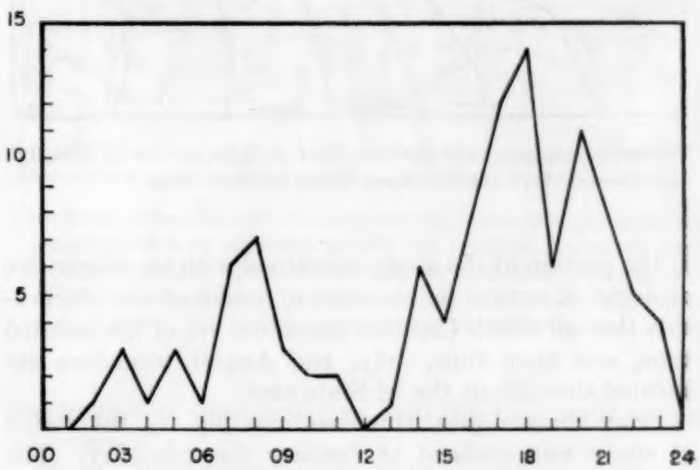

FIGURE 1.—Tornado occurrences relative to time of day for the years 1950 through 1955, January through August, for Alabama, Georgia, and South Carolina.

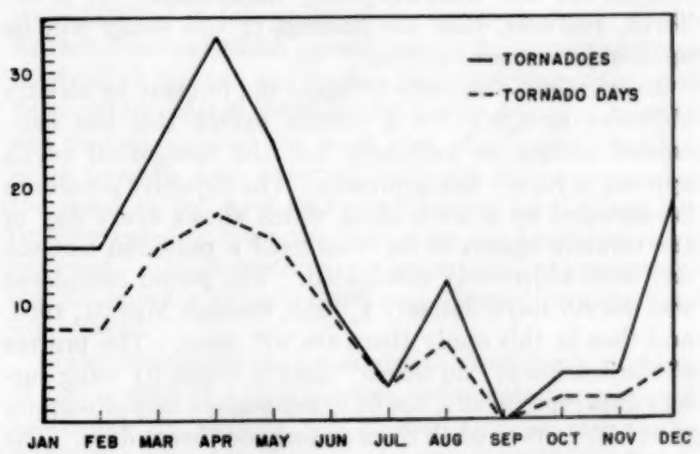

FIGURE 2.—Tornado occurrences plotted by months for the years 1950 through 1955 for Alabama, Georgia, and South Carolina.

Tornadoes were classified first as "family" and "isolated" types. While there is not sufficient evidence to prove the point, it seems likely that isolated tornadoes may be less intense. This classification, while not used

[1] Project sponsored by U. S. Weather Bureau.

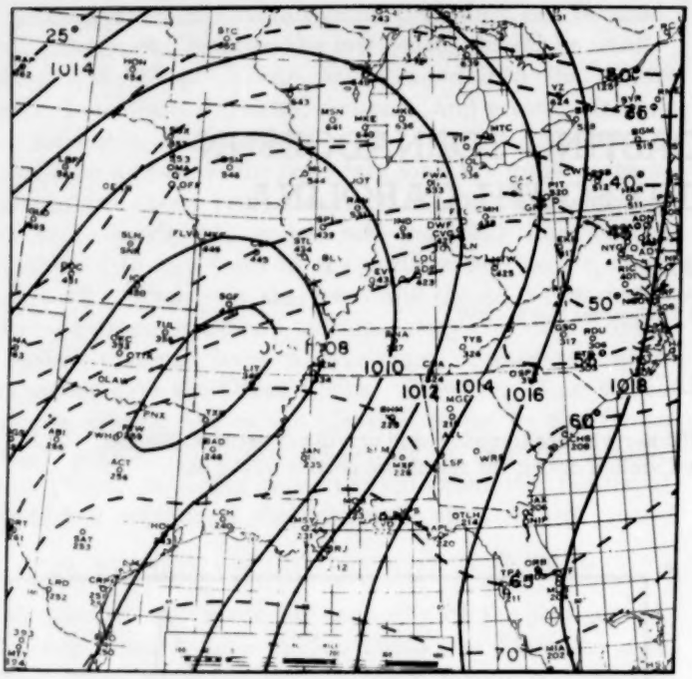

FIGURE 3.—A composite surface chart at 0130 EST for 10 "family" type tornado cases in the tri-State area.

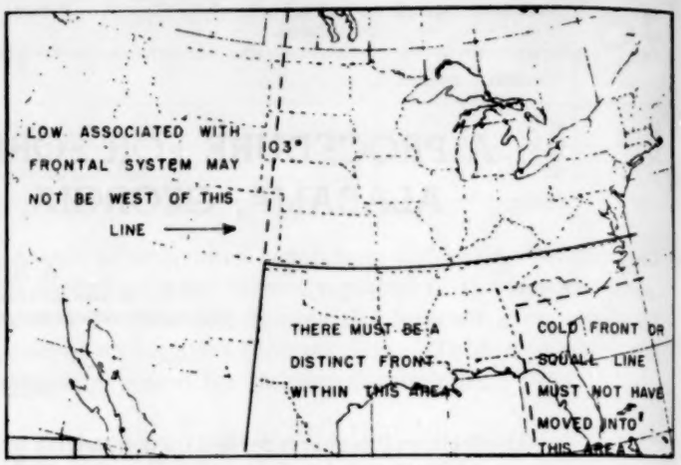

FIGURE 4.—Reference chart to be consulted when evaluating the surface cyclone and frontal positions on the 0130 EST chart. In order for a surface cyclone to be in a position favorable for tornadoes in the tri-State area it must be centered east of 103° W., and a portion of the front must lie within the area bounded by the solid lines along latitude 36.5° N. and longitude 103° W. Cold fronts or squall lines which are east of Atlanta, Ga., on the 0130 EST map preclude tornado activity on that day.

in the portion of the study concerned with an affirmative or negative answer on occurrence, produced the observation that all South Carolina tornadoes are of the isolated type, and that June, July, and August tornadoes are isolated throughout the tri-State area.

From climatological considerations (fig. 2), the period of study was confined to January through May. The reason for omission of June, July, and August from the tornado season is obvious from figure 2. Data were not available for September through December. These months are also climatologically unfavorable. It is believed, however, that the findings of this study will be applicable to these months.

Every effort was made to make the forecast by strictly objective criteria. To a certain extent this has been carried almost to extremes, but the categorical result appears to justify this approach. The objective procedure is expressed by a work sheet which allows every day of the tornado season to be considered a potential tornado day until objectively eliminated. The period considered was the 907 days, January 1, 1950, through May 31, 1955, and thus in this study there are 907 cases. The process of elimination of "no threat" days is begun by using surface data; specifically, the 0130 EST surface map eliminates about 75 percent of all days as tornado-threat days. The detailed discussion follows.

2. SURFACE CHART

The dewpoint over the area in which tornadoes occur has previously been recognized as an important criterion. Rather than to attempt to forecast the dewpoint at a location in the area, when the desired location is unknown, a large area was considered on the 0130 EST surface chart. If the dewpoint was 60° F. or more at any station along the Gulf coastal area from Biloxi, Miss. eastward to Jacksonville, Fla., or anywhere in the tri-State area, the first criterion for a tornado was met. This rule had no exception in the 907 cases.

The lowest value of the surface pressure observed in the tri-State area on the 0130 EST surface chart proved to be of real significance in separating cases. It was found that no tornadoes occurred when the lowest surface pressure in the tri-State area was 1018 mb. or above. This finding, combined with the dewpoint requirement above, eliminated 449 days from further consideration.

A composite surface chart of ten "family" type tornado days is shown in figure 3. From this chart a general idea of the location of frontal positions can be deduced as being associated with the general trough through Arkansas and Texas. The exact location of each front at 0130 EST was plotted on a separate map for each tornado date. These maps showed a wide variety of pattern, but several general features were noted. In every case, a definite frontal system was present within the area south and east of 36.5° N. latitude and 103° W. longitude, as shown in figure 4. In most cases it was a cold front. In quite a few cases there was an active squall line, and in many others there was a definite Low within or just south of the area. Conversely, in no case was the Low, in which the frontal system was located, centered farther west than 103° W. Also, the cold front or squall line should not have passed into the southeastern quadrant of Atlanta, Ga. Almost all cases had a portion of the frontal system, of the low center, south of the latitude of Atlanta. Hence, if a frontal system on the 0130 EST surface chart did not meet these limitations, the date became negative for

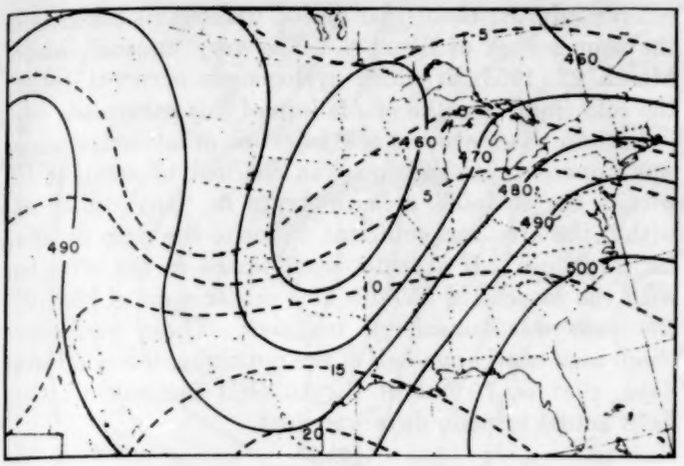

FIGURE 5.—A composite 850-mb. chart of 10 "family" type tornado dates using the 2200 EST data for the previous day. Solid lines are contours. Dashed lines are isotherms.

tornadoes. A single exception appeared on May 31, 1953, when a doubtful tornado was reported 200 miles from the nearest low cloud observation, and even farther from the nearest front. Lack of fronts in the proper area eliminated 186 additional days.

The following criterion would be unnecessary except that in this study pure objectivity was the aim. After eliminating those days when the pressure was too high, the dewpoint too low, or the fronts failed to qualify, there remained some cases regarding which any forecaster would say, "This isn't the proper situation principally due to the character of the flow over the southeastern United States." These cases were eliminated by measuring the gradient and geostrophic flow in the area, or in the warm sector, if a front divided the area. The angle which the surface isobars on the 0130 EST chart made with north was measured. In cases where this was changing, the average was taken. Any case for which the geostrophic flow (direction of the isobars) over the States of Alabama, Georgia, and South Carolina was from north of 260° or 130°, was made a negative tornado date. On the charts used, the gradient winds (strongest wind in the lower 3,000 ft.) were plotted from the 2200 EST pilot balloon runs. All dates when those winds in the tri-State area, or immediately adjacent such as at Tallahassee, Fla., indicated the flow was between 270° and 130° inclusive through north were eliminated from further consideration as a tornado day. These considerations had no failures, and reduced the tornado threat days by another 41 cases.

Only 230 favorable days remained to be considered, and for these, upper-level factors were applied.

3. 850-MB. LEVEL

Figure 5 is a composite 850-mb. chart of ten "family" type tornado days. A feature to be noted is the orientation of the contours over the tri-State area. Another feature is the divergence of the isotherms over this area

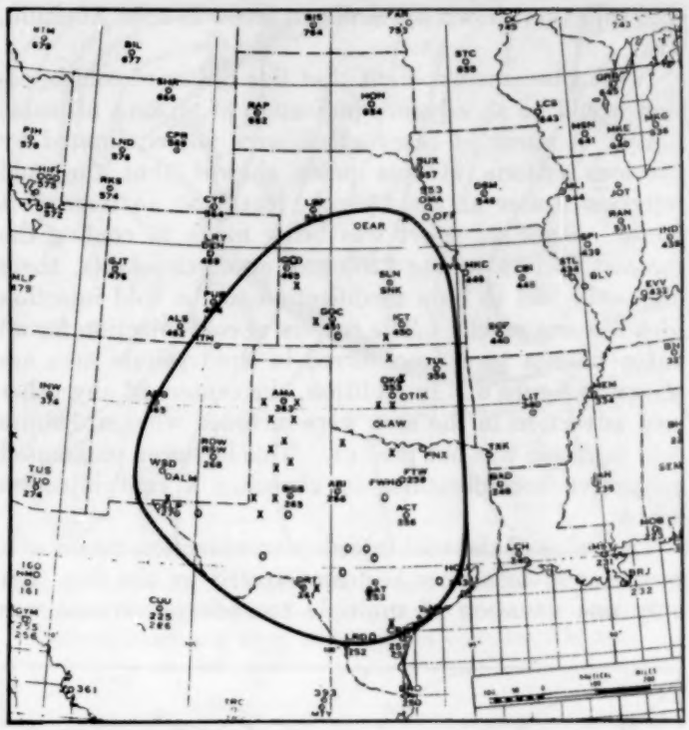

FIGURE 6.—Geographical area in which the center of a cold injection or apparent cold advection at 850 mb. must be located at 2200 EST in order for tornadoes to form in Alabama, Georgia, and South Carolina during the following day. "x" marks cold injection centers. "o" marks apparent cold advection centers.

in contrast to their crowding over the Panhandle region of Texas.

Beebe [2] used the contour which passed over Atlanta, Ga. on the 850-mb. chart as a parameter in forecasting precipitation for Atlanta. Since Atlanta's location is representative within the tri-State area, this same idea was examined in this study of the upper-air data. If the 850-mb. contour which passed over Atlanta reached into the Gulf of Mexico, and surface factors were positive, the date was considered favorable for a tornado day. Usually the contour entered the coast east of Mobile, Ala., but some tornado days occurred with the contour reaching the coast as far west as Lake Charles, La. When the contour failed to cross the Gulf coast, no tornadoes were expected. This consideration eliminated 67 of the remaining 230 possible tornado days, and 5 actual tornado days were lost.

Many forecasters are familiar with the difficult problem of cyclogenesis and with the forecasting solution proposed by George [5]. Briefly, this method requires as a predecessor, the existence of what he terms a "cold injection," which consists of a current at 850 mb. (usually narrow and at times ageostrophic) crossing isotherms at an angle somewhere near to perpendicular and extending over a thermal range of at least 12° C. The center of cold injection is defined as the mean temperature spanned by the cross-isotherm flow at the center of the current. Figure 12 may be used as an example; the center of the

cold injection shown by the open arrow is near Amarillo, Tex.

It soon became apparent that this center of cold injection would be an advance indication of an area of instability. A check of cases which were not eliminated by previous criteria at this point showed that the cold injection center at the 850-mb. level was an important factor. Since an effort was being made to confine the forecast factors to the 2200 EST upper-air charts, there obviously had to be a modification to the cold injection idea to some extent. The centers of cold injection for all dates when a tornado occurred in the tri-State area are shown in figure 6. In addition, the centers of any other cold advection in the area were included when a definite cold injection was not present. This inclusion eliminated subjective considerations in choosing a cold injection center.

The value of the cold injection or advection center as a predictor of tornadoes is demonstrated by the fact that only one situation of multiple tornado occurrence was recorded during the 6-year period without its presence in the proper area of figure 6. The very unusual case of March 22, 1953, in which cyclogenesis occurred behind the cold front, was the one failure of this parameter.

In those cases where a cold injection or advection center was apparent, its location was checked to see if it fell within the enclosed area in figure 6. Any center not within the area was sufficient to make the date negative for tornadoes. If a center was located in the area, but with the associated 850-mb. low center west of 103° W., the case was considered negative. These parameters eliminated nearly one-half of the remaining tornado threat days, that is, 76 out of the 163 left for consideration. Four actual tornado days were lost.

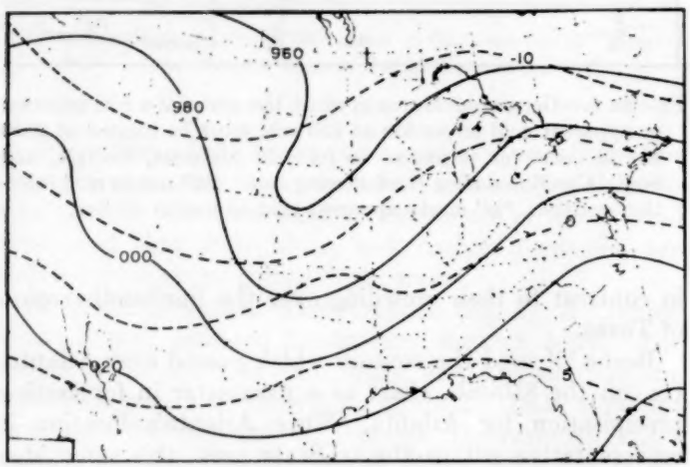

FIGURE 7.—A composite 700-mb. chart of 10 "family" type tornado dates using the 2200 EST data for the previous day. Solid lines are contours. Dashed lines are isotherms.

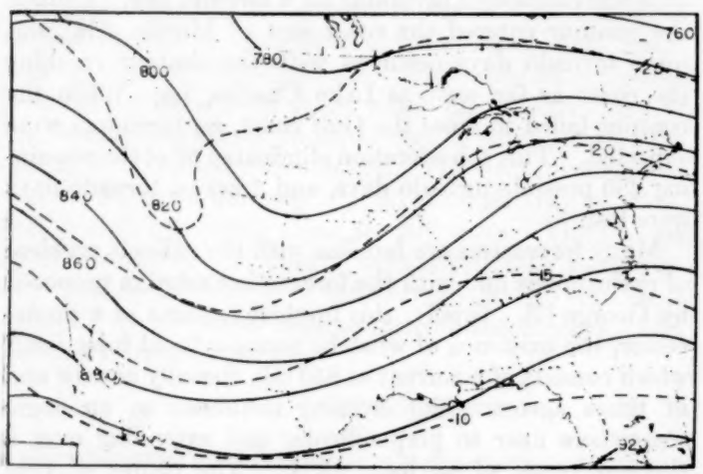

FIGURE 8. A composite 500-mb. chart of 10 "family" type tornado dates using the 2200 EST data for the previous day. Solid lines are contours. Dashed lines are isotherms.

4. 700-MB. CHART

The composite 700-mb. chart of ten days when tornadoes of the "family" type occurred is shown in figure 7. No important criteria were developed from this level.

5. 500-MB. CHART

Ten "family" type tornado days were utilized in making the composite 500-mb. chart shown in figure 8. At this level it was found that whenever the trough line was located east of the Mississippi River, south of the Ohio River, no tornadoes occurred. A trough line as used here means a more or less north-south line followed by winds at this level of 270° or more northerly direction on the west side. (Note. Very minor perturbations were not considered.) This eliminated 7 days after lower-level criteria had remained favorable for tornadoes.

6. EXAMPLES AND REMARKS

Figure 9 shows the 0130 EST surface map of January 2, 1953. A similar surface map at 0130 EST on January 23, 1953 is shown in figure 10. The dewpoint condition was the only surface criterion for tornadoes missing from the chart in figure 9—the highest dewpoint observed within the tri-State area or in the group of stations from Biloxi, Miss. to Jacksonville, Fla. was 55° F. At Mobile, Ala. in figure 10 the dewpoint was 62° F. On January 23 there occurred a tornado in Alabama. No record of severe storms is found on the date of January 2.

To illustrate the effectiveness of the method outlined here, two different dates have been considered. The matter of time of year is eliminated by using the same date, February 20, in 1953 and 1954. Shown in figure 11 is the pertinent portion of the 0130 EST surface map in 1953 and in figure 15 the corresponding map in 1954. Both maps meet all surface requirements. In figure 12 is the 850-mb. chart associated with the surface chart in figure 11. The cold injection is quite distinct and the center is within the area outlined in figure 6. The contour on the 850-mb. chart (fig. 12) over Atlanta reaches the Gulf near Tallahassee. The same requirements are met for the 850-mb. chart for 1954 shown in figure 16

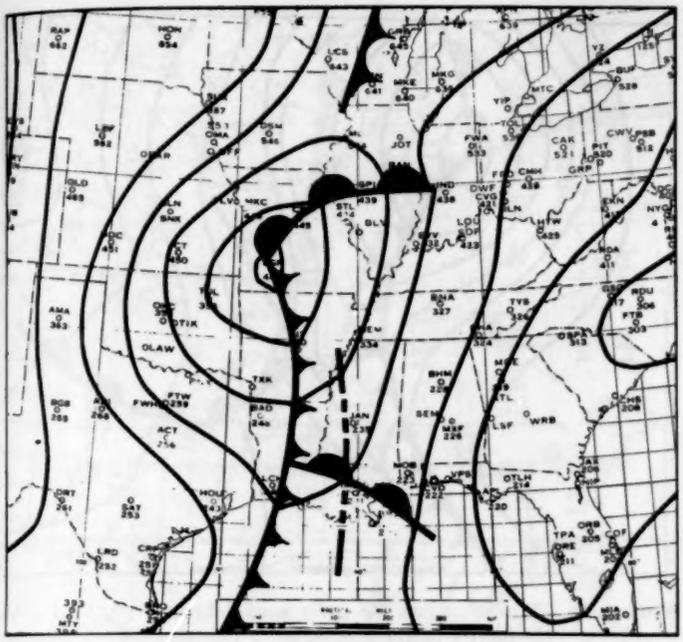

FIGURE 9.—Surface chart for 0130 EST, January 2, 1953. 55° F., at Biloxi, Miss., was the highest dewpoint within the tri-State area or the area from Biloxi to Jacksonville, Fla. All other surface criteria for tornadoes were met. No tornadoes were reported in Alabama, Georgia, or South Carolina on this date.

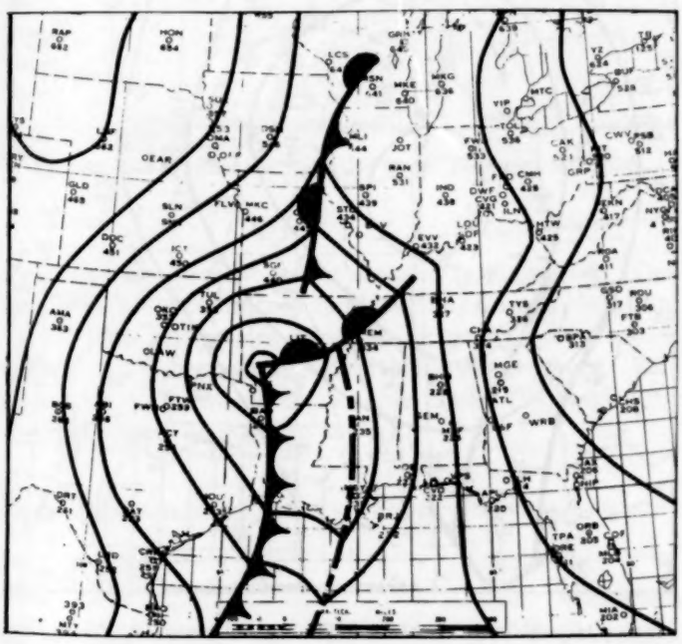

FIGURE 10.—Surface chart for 0130 EST, January 23, 1953. The dewpoint at Mobile, Ala., was 62° F. All other criteria for tornadoes were met. A tornado occurred in Clarke County, Alabama on this date.

which is the companion chart for figure 15. The 500-mb. charts did not show the trough line east of the Mississippi River on either of these two dates. Thus all criteria are favorable for a tornado forecast.

In figures 13 and 14 are shown portions of the 1330 and 1930 EST surface charts for February 20, 1953. A

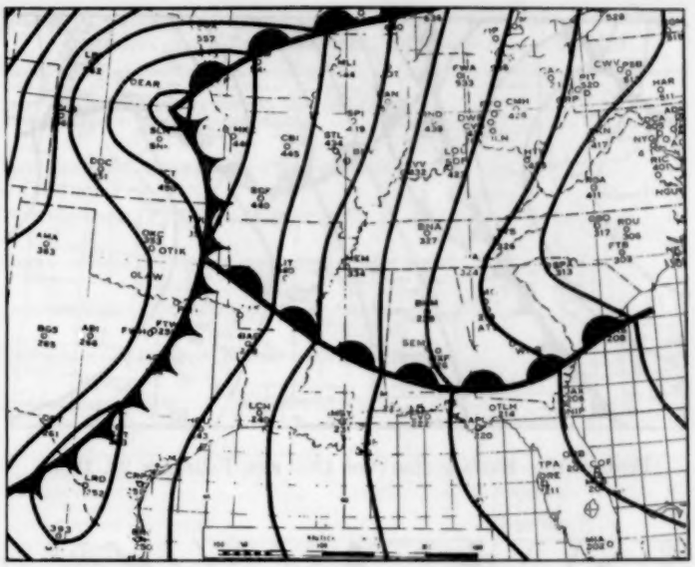

FIGURE 11.—Surface chart for 0130 EST, February 20, 1953. All criteria were favorable for tornadoes. Tornadoes occurred in Colbert, Marion, Walker, and Franklin Counties, Alabama.

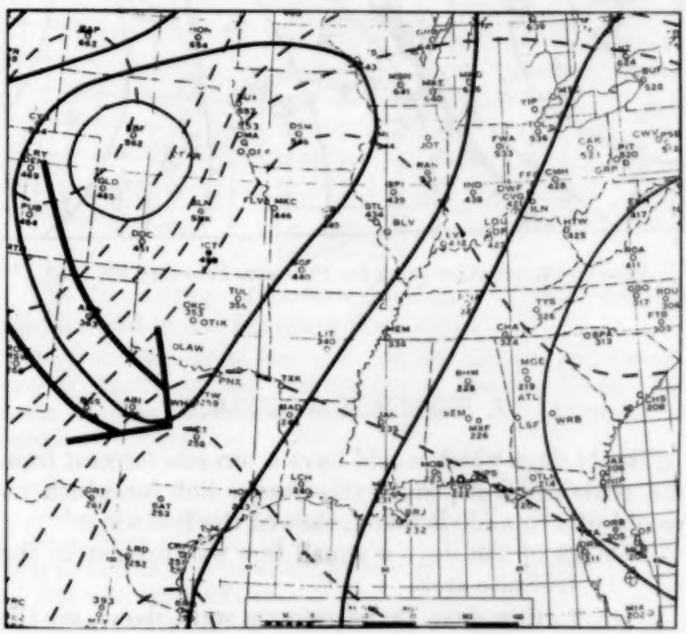

FIGURE 12.—850-mb. chart for 2200 EST, February 19, 1953. 200-ft. contours are shown as solid lines. Isotherms at 5° C. intervals are shown as dashed lines. The cold injection is shown by the open arrow.

family of four tornadoes was reported in west-central Alabama between 1730 and 2000 EST.

In figures 17 and 18 are shown portions of the 1330 and 1930 EST surface charts for February 20, 1954. Although the vicious line squall lasted until between 1330 and 1930 EST, and a tornado was reported in eastern Mississippi at 0235 EST, this case is recorded as a "miss" in this study. No record of a tornado is in the data for Alabama, Georgia, or South Carolina.

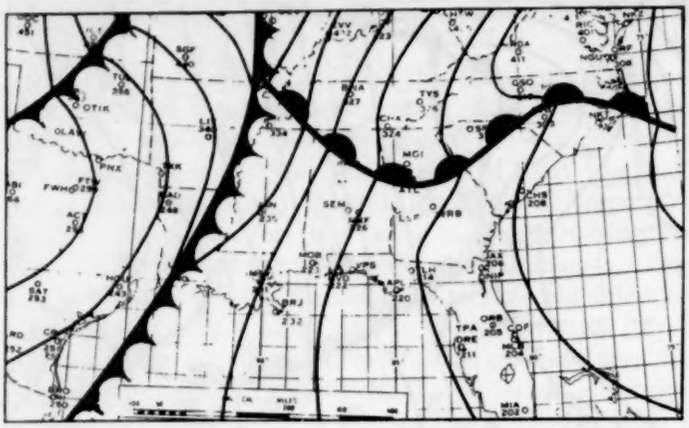

FIGURE 13.—Surface chart for 1330 EST, February 20, 1953.

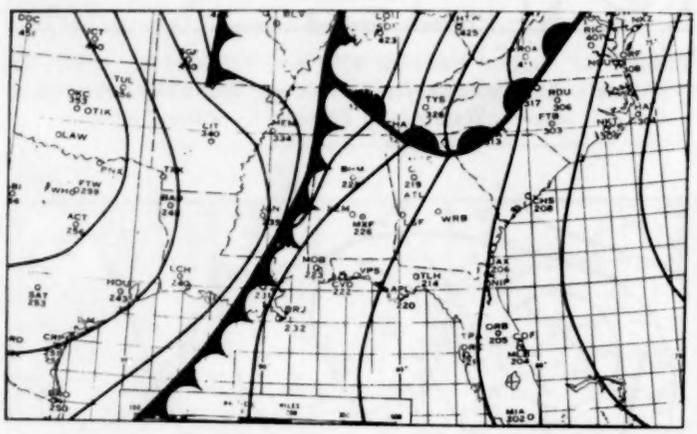

FIGURE 14.—Surface chart for 1930 EST, February 20, 1953.

7. FORECAST ACCURACY

The 41 days which would have a tornado forecast from the criteria developed in this study, but for which no record of a tornado is found, showed the following:

On 28 of the days a squall line was present in the tri-State area.

On 7 other days thunderstorms were shown on the 6-hourly synoptic charts.

On 4 additional days thunderstorms or a squall line affected an immediately adjacent area.

On 2 days only an active cold front without thunderstorms was shown on the 6-hourly charts.

This tabulation indicated that 97.5 percent of all tornado forecasts made by this method resulted in severe weather and 48.7 percent in tornadoes.

There were 10 tornado situations which this study missed by forecasting "no tornado". Mention has already been made of two of these; the dubious one at Cottageville, S. C., and the unusual case of cyclogenesis on March 22, 1953. Another date would have been correct from a practical sense, as the severe weather area was very limited in extent to only the Mobile Bay area and the storm occurred at 0245 EST. Six of the other seven were the "non-family" type of single occurrences. In only four cases would this study have led to misleading and damaging forecasts from a practical sense.

It was noted during the study that the time of occurrence was usually when the squall line passed, or if no

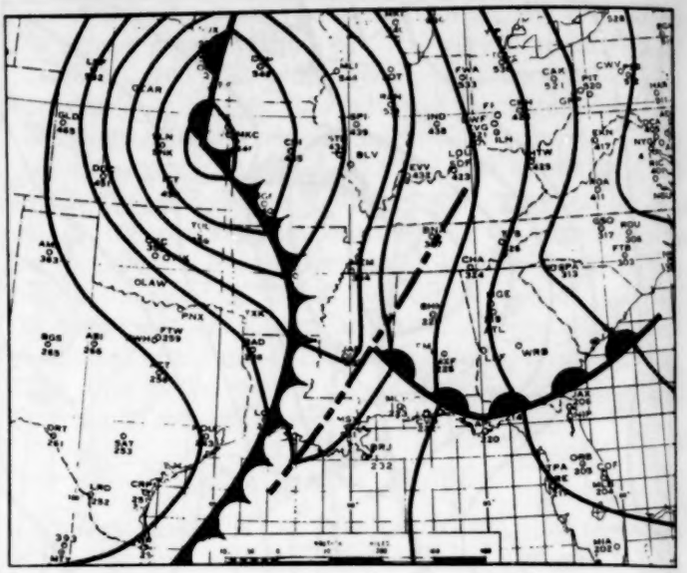

FIGURE 15.—Surface chart for 0130 EST, February 20, 1954. All criteria were favorable for tornadoes. Tornadoes were reported in Lamar, Covington, Jones, Newton, and Neshoba Counties, Mississippi. None occurred in Alabama, Georgia, or South Carolina.

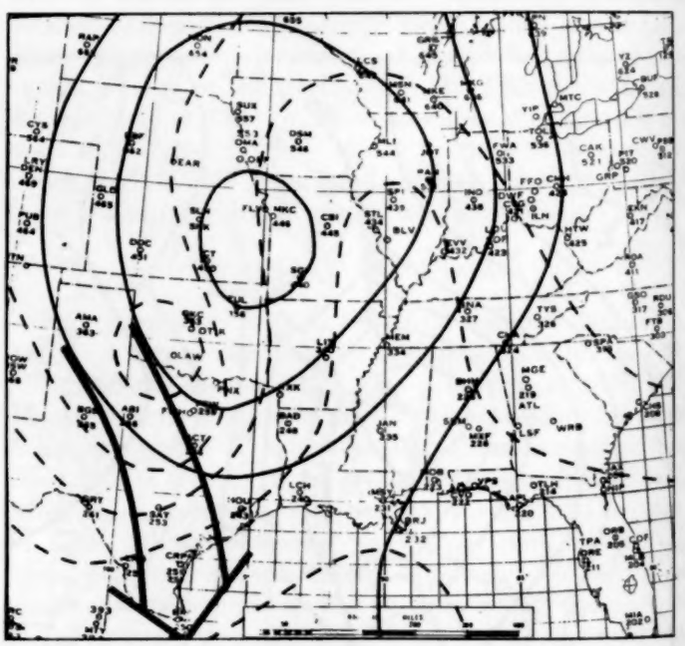

FIGURE 16.—850-mb. chart for 2200 EST, February 19, 1954. Contours are solid lines; isotherms, dashed lines. The cold injection is shown by the arrow.

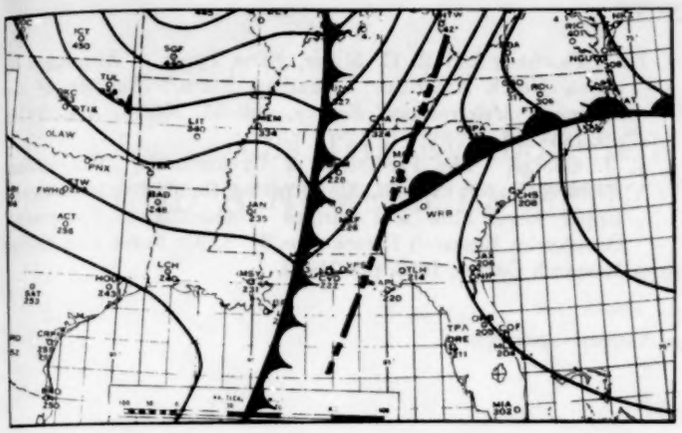

FIGURE 17.—Surface chart for 1330 EST, February 20, 1954.

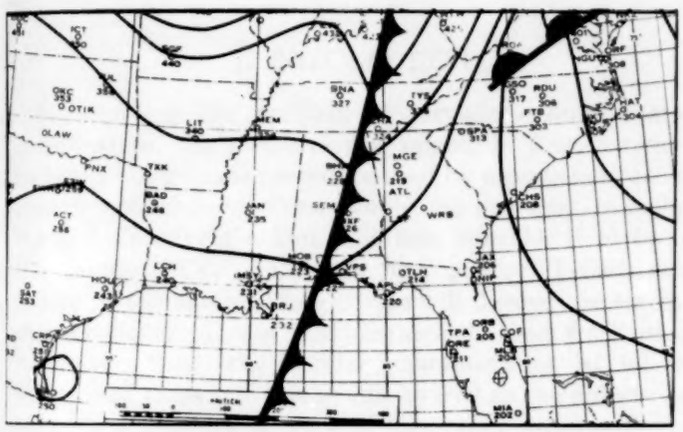

FIGURE 18.—Surface chart for 1930 EST, February 20, 1954.

squall line was present, when the cold front passed. This usually eliminates much of the area due to frontal location.

The 1955 data were used as an independent check initially, and then combined with the other years. The results for 1955 are given in table 1 and the results for combined years 1950–55 in table 2.

TABLE 1.—*Results of application of forecast procedure to independent data, January–May, 1955*

Tornado days forecast	10	
Forecast correctly	8	(80.0 percent)
Actual tornado days	11	
Forecast correctly	8	(72.7 percent)
No tornado days	139	
Forecast correctly	137	(98.5 percent)
All days considered (incomplete data on one day)	150	
Forecast correctly	145	(96.6 percent)

		Forecast		
		Tornado	No tornado	Total
Observed	Tornado	8	3	11
	No tornado	2	137	139
	Total	10	140	150

TABLE 2.—*Results of application of forecast procedure to combined dependent and independent data, January–May, 1950–55*

Days considered—January through May 1950–55		907
Data from upper air charts unavailable		1
		906
Days eliminated by dewpoint and pressure from surface chart		449
		457
Days eliminated by fronts not in proper area		186
		271
Days eliminated by improper gradient/geostrophic winds		41
		230
Days eliminated by 850-mb. contour over Atlanta		67
		163
Days eliminated by no cold injection or improper location		76
		87
Days eliminated by 500-mb. trough too far east		7
		80

Tornado days forecast	80	
Forecast correctly	39	(48.7 percent)
Actual tornado days	49	
Lost by surface parameters	1	(Cottageville, S. C.)
	48	
Lost by 850-mb. parameters	9	
Successfully forecast	39	
Actual tornado days	49	
Forecast correctly	39	(79.5 percent)
No tornado days	858	
Forecast correctly	817	(95.2 percent)
All days considered	906	(Incomplete data on one day)
Forecast correctly	856	(94.5 percent)

		Forecast		
		Tornado	No tornado	Total
Observed	Tornado	39	10	49
	No tornado	41	816	857
	Total	80	826	906

8. WORK SHEET

The forecasting procedure developed in this study is summarized in the following work sheet:

Use 0130 EST surface map and 2200 EST 850-mb. and 500-mb. charts. Assume tornado alert for area of Alabama, Georgia, and South Carolina for the date until a "STOP" item is reached in right hand column.

STOP

1. If dewpoints of at least 60° F. or more are not found within the tri-State area nor on BIX–JAX line of stations, check STOP _____
2. If no surface pressure within tri-State area is lower than 1018 mb., check STOP _____
3. If there are no fronts in proper area in fig. 4, check STOP _____
4. If direction of geostrophic flow over area is 270° through north to 130°, check STOP _____
5. If gradient winds in tri-State area at 2200 EST (including TLH) are from 270° through north to 130°, check STOP _____
6. If the 850-mb. contour through Atlanta does not reach the Gulf coast, check STOP _____
7. If a center of cold injection or cold advection exists over lower Great Plains area at 850-mb., check area shown in fig. 6:
   - A. If center is outside of area, check STOP _____
   - B. If there is closed Low at 850 mb. associated with the injection and centered west of 103° W., check STOP _____
8. If the portion of the 500-mb. trough south of the Ohio River is east of the Mississippi River, check STOP _____

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3. E. J. Fawbush and R. C. Miller, "A Mean Sounding Representative of the Tornadic Airmass Environment," *Bulletin of the American Meteorological Society*, vol. 33, No. 7, Sept. 1952, pp. 303–307.
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ON THE EVALUATION OF TORNADO REPORTS AND A NUMERICAL METHOD FOR THEIR CLASSIFICATION[1]

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ABSTRACT

An attempt is made to rationalize the spectacular increase in the number of tornado reports during recent years and to make a logical segment of these reports compatible with reports of previous years. A numerical method of classifying tornado reports into "tornado," "possible tornado," "severe local storm," and "local storm" is suggested.

1. INTRODUCTION

In studying the problem of tornado definition and classification, the meteorologist might, at first, attempt to follow the general procedure used by scientists in other branches of science. For example, the zoologist, in defining and classifying a lion, will first consider it to be in the family "Cat", then in the genus "Felis", and finally in the species "Leo". He will discuss the similar characteristics of cats that distinguish them from other mammals; then, the similar characteristics of felines that group them into one genus, as well as the differences between the genus Felis and the other genera in the cat family. And finally, he will classify the Leo species on the basis of its individual properties as well as its differences from other species in the genus Felis. When a particular animal is brought to the zoologist he is able to identify it by noting its similarities and differences from other animals and thus assigns to it a specific family, genus, and species.

Similarly a scientific classification and definition of "tornado" can be set up in somewhat this manner: A tornado belongs to the family "storm", to the genus "severe local storm", and the species "tornado". Without going into the details of the description of the properties of the family and genus, we might, if we so wished, set up a definition of the species "tornado" based on the fact that it is a rotating vortex, that it has reduced pressure in the center, that frequently it has been observed in the right rear quadrant of a cumulonimbus cloud, that it has a particular velocity profile, that it is formed in a micro-Low, etc., etc.

This would make a very interesting and undoubtedly an accurate classification. Unfortunately, it would not prove to be too useful. Unlike the usual problems in scientific classification, the storm that is to be classified cannot be brought to the scientist for his inspection and for his study of its similarity and differences to other species of its genus and family. In the case of tornado classification and identification, these must be made usually on the basis of hearsay reports. From this point of view, the problem with which we are faced is somewhat similar to the problem of the interpretation of flying saucer reports. In these the scientist must consider and evaluate only the *reports* that are submitted to him, and he must form a conclusion based on these *reports*.

With regard to the tornado reports, we must fully realize that they are provided to us by laymen who are not trained in meteorological phenomena; by laymen who, for the most part, have just lived through a most violent kind of storm experience and thus whose objectivity with regard to what they saw or what happened is limited; by newspaper accounts of storms which on one hand are based on observations by laymen and on the other are "flavored" to make interesting reading for the public. In a few instances—and these are so few in number that a general classification method can hardly be based on them—qualified observers, such as meteorologists or field survey teams, have gone into the area where the storm occurred and have tried to evaluate what happened. But even these reports have yielded doubtful conclusions in many instances.

2. STATISTICS

Keeping in mind that tornado statistics emanate from such unreliable sources, let us look at what these statistics are:

On figure 1 there is given by the heavier line the number of tornado reports per year for the period 1916 to 1956. These reports are based on the official annual summaries put out by the Office of Climatology of the U. S. Weather Bureau. We note that the curve continues in a jagged fashion until about 1948 or 1949, when a progressive climb begins and continues in a most determined manner. On the right hand side is indicated the range of reports

[1] Presented at the panel discussion, "Tornado Climatology", American Meteorological Society Conference on Severe Local Storms, April 16, 1957, Kansas City, Mo.

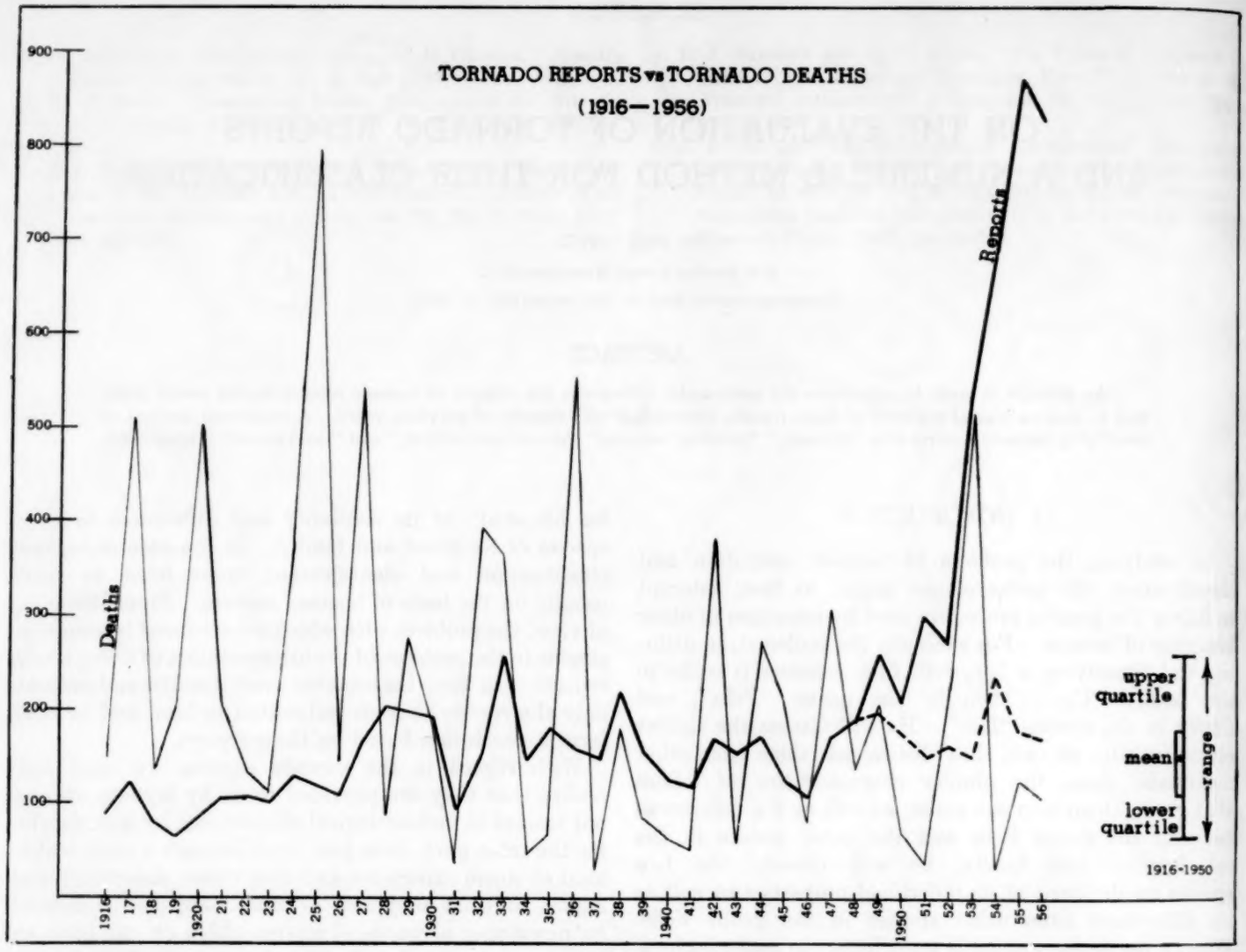

FIGURE 1.—Tornado reports and tornado deaths (1916–1956). Range, upper quartile, lower quartile, and mean of tornado reports are given in diagram, lower right. Dashed line after 1948 shows adjusted reports based on table 2.

from 1916 to 1950, as well as the upper quartile, the lower quartile, and the mean. Consequently, the rectangle on the side of the vertical line represents the range of the middle 50 percent of the cases. From 1916 to 1950, the range is between, roughly, 50 and 250, with the mean about 150 tornado reports per year. But, beginning in 1948 and thereafter, the number of tornado reports exceeds 300, 400, 500, until 1955 and 1956 when it exceeds 800.

The first obvious conclusion that might be drawn from a curve of this sort is that we have had more tornadoes in the past 8 or 10 years than we had during any other period in the past 40 years. If this were so, we should expect that the number of tornado deaths would increase as well. But we notice that the tornado death curve, which is given by the thin line, does not show any such spectacular increase during the past 8 or 10 years.

These data can be viewed a little bit better if we smooth out the high peaks, which represent particularly striking years, by means of 5-year running means. Figure 2 shows these means.

We see in figure 2 that the tornado report curve is now almost completely smoothed out until about 1948 and 1949, when the curve begins to climb and is quite high during the 5-year period ending 1956. On the other hand, the tornado death curve remains more or less the same as it was during the past 40 years.

We suspect, therefore, that while the *number of reports* has increased during the past 8 years, the actual number of tornadoes needs not necessarily to have increased as well. We may then ask: "To what may we attribute this increase of tornado reports?" First, let us look at what has happened since 1948 in this field, and see what are the events that might be related to this increase in tornado reports.

In 1948 Tinker Field was struck twice within the same month by tornadoes causing a considerable amount of damage. At that time, the Air Force established the

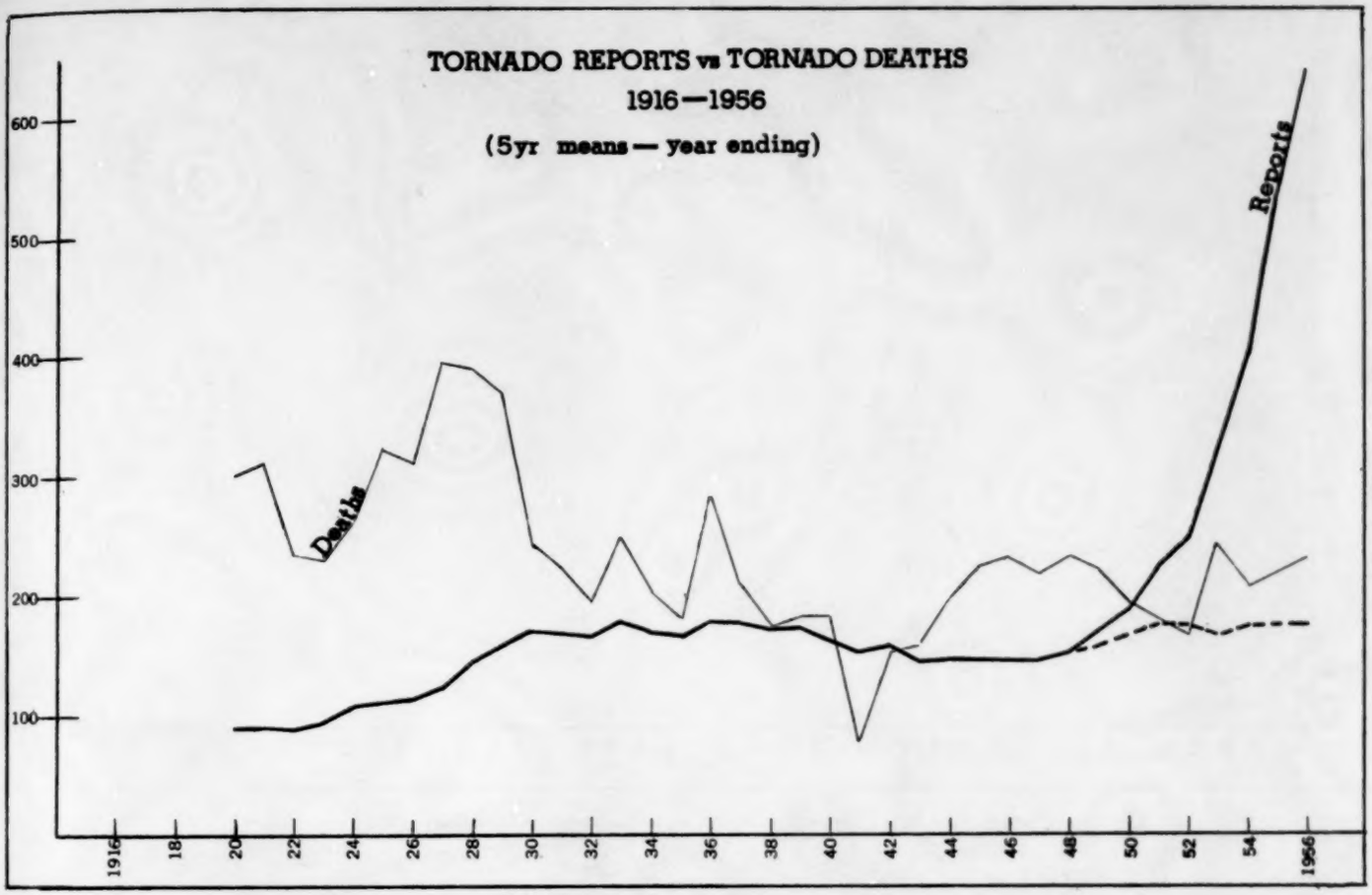

FIGURE 2.—Five-year means of tornado reports and tornado deaths (1916–1956). Dashed line after 1948 indicates adjusted reports based on table 2.

Severe Weather Warning Center under Fawbush and Miller, who were given the responsibility of forecasting tornadoes for the Air Force bases, in order to try to eliminate a repetition of this type of damage.

In 1950 a severe local storm network of observation stations was established in the vicinity of Washington, D. C., for the purpose of studying pressure jump lines and the relation of these lines to severe local storms. In 1951 this network was transferred to the severe local storm belt in the Midwest where it has been since. Associated with the establishment of this network, a press clipping service was procured to give detailed information about severe local storm occurrence in the research network area.

In 1952, the Weather Bureau established, first in Washington, and later transferred to Kansas City, the SELS Forecast Center for the purpose of coordinating and integrating tornado and severe local storm forecasts.

In 1953, the press clipping service was extended to the eight major tornado States in the Midwest, and in 1954 to all States east of the Rocky Mountains. At the same time a special reporting form called "Form 614–4" was sent out to all State Climatologists to assist in the completion of additional information about the nature of storms. In 1955 the severe storm reporting Form 614–4 was replaced by 614–5, which was a much more complete form and requested much more detailed information about severe storms. In 1956 the situation was about the same.

Also, during this period extensive research on severe local storms and tornadoes was initiated and pursued not only in government agencies but also in academic institutions (among which are Texas A. and M. College, University of Chicago, St. Louis University, and Oklahoma A. and M. College).

Thus, in recent years there has been a considerable amount of technical activity in the field of severe local storms and tornadoes. In addition, there has also been provided an additional and very fruitful source of severe storm reports, in the form of the press clipping service. There is another interesting and auxiliary proof of the growth of interest in tornadoes during this period, and this is provided in figure 3. This is a 5-year running mean of the number of publications on tornadoes as listed in *Meteorological Abstracts and Bibliography* of the American Meteorological Society. We see that this curve, too, shows a remarkable increase beginning in 1948 and 1949 and continuing through 1954, the last year for which more or less complete data are available.

Our conclusion, therefore, is that due to the increased interest in the problem, and due to the increased facilities for the accumulation of reports, the number of *reports* of

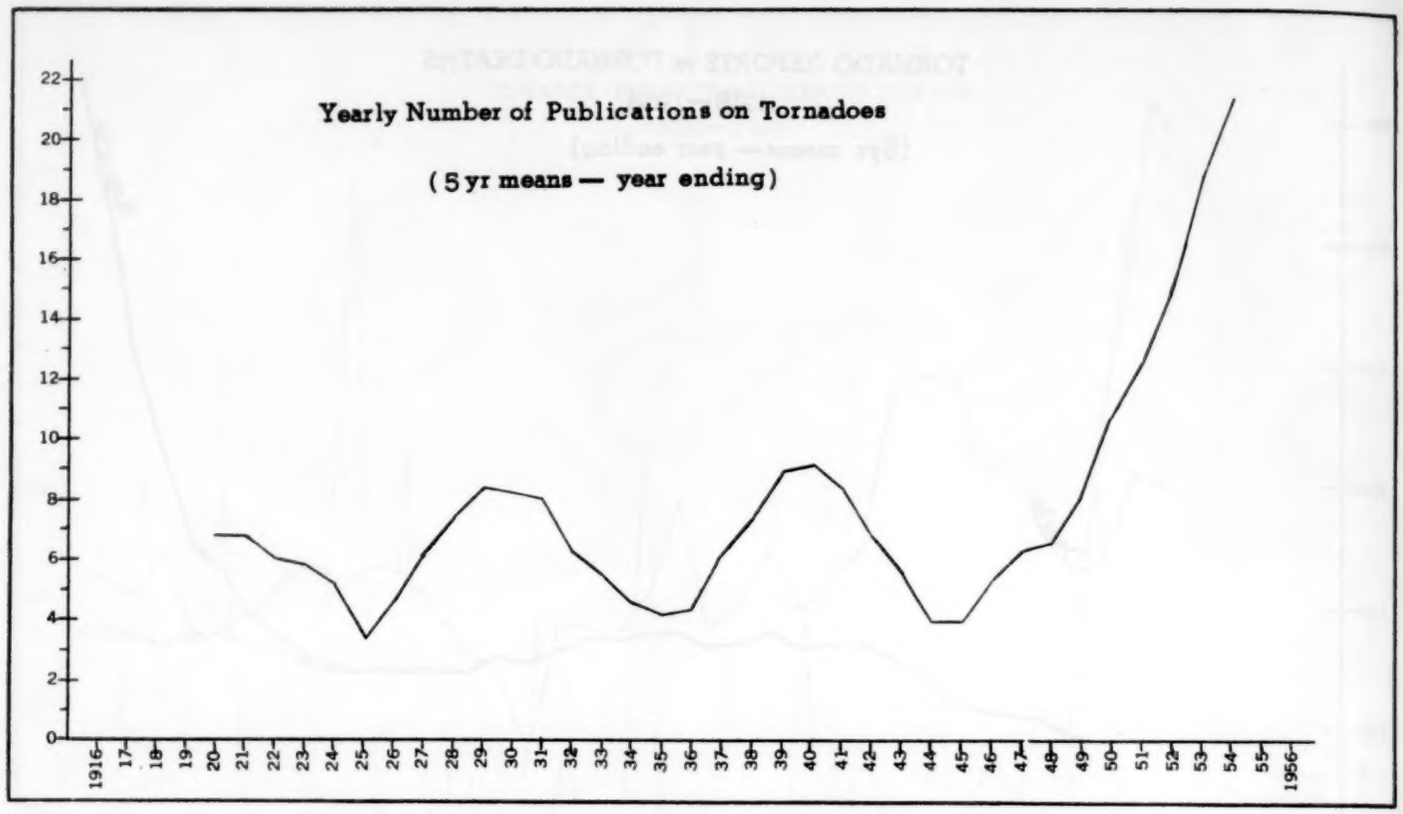

FIGURE 3.—Annual number of publications on tornadoes (5-year means).

tornadoes has been steadily increasing during the past 8 to 10 years. On the other hand, we have found no evidence on which to base an hypothesis that the number of actual tornadoes has increased.

In this regard, it would be pertinent to refer to a statement from the Final Report (dated March 1957) of the Tornado Damage Survey Project conducted by the Research Foundation at Oklahoma A. and M. College and sponsored by the U. S. Weather Bureau: " . . . in areas where severe storms have been forecast, many more tornadoes are reported. These investigations indicated that most of these reported tornadoes were lightning shadow, virga and/or scud-type cloud fragments." It should be kept in mind that active forecasting of tornadoes began in 1948 by the Air Force and in 1952 by the U. S. Weather Bureau.

3. RATING OF TORNADO REPORTS

The next problem is how to evaluate the tornado reports of recent years in order to make them compatible with the tornado reports which preceded them.

After reading literally hundreds of tornado reports which have been submitted during the past 10 years, the author was struck by the fact that certain reporting items appear to be more significant than others. As a matter of fact, there emerged a certain pattern of the relative importance of the various tornado reporting items. Unfortunately, there was no way to evaluate this relative importance objectively, so that at this stage only a subjective rating schedule can be offered, but nonetheless, a schedule based on a considerable amount of experience with tornado reports. This schedule of relative importance of tornado reporting items has been set up in the form of a table and listed in the order of importance in table 1.

To the right of each of the items is indicated a relative numerical rating. The author can justify neither the specific individual rating, nor its specific relative value other than by saying that this is what they appear to him. Certain items have been given the same relative ratings, and others have not. Still other items, such as rotation and wind speed have been omitted since they did not seem to be reliable reporting items. If a rating schedule such as this is adopted it is felt that with practice and use, a better and more objective system will eventually emerge. This, then, should be considered as a first attempt in the evaluation of tornado reports. Let us adopt this rating schedule for the moment and proceed to the next step.

Every reported storm listed as a tornado in the monthly

TABLE 1.—*Proposed numerical ratings of tornado reports*

a. Funnel observed	100
b. Distinctive noise	50
Total destruction	50
Extraordinary damage	50
c. Explosive-type damage	30
Narrow path (≤¼ mile)	30
Skipping action	30
d. Twisting-type damage	20
Lifting of objects	20

TABLE 2.—*Number of tornado reports in severe local storm rating groups 1941–56, based on numerical ratings in table 1. For explanation of heavy line see text*

Rating	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956
0	26	39	45	49	37	26	50	57	66	80	104	45	88	157	161	98
10																
20	1			1		1	4	1	3		6	1	4	18	9	8
30	33	39	24	28	25	35	50	63	71	65	73	73	120	115	92	82
40										1	1	4		1		1
50	6	3	8	7	10	8	19	22	35	4	21	24	38	30	44	35
60	2	1	5			1	3	5	6	4	10	3	7	12	9	15
70	2		1			1					3		3	5	10	1
80	7	6	9		9	8	25	32	36	14	11	26	60	43	48	42
90											1			1	2	1
100	4	13	4	2	15	11	9	18	33	26	66	58	145	210	251	356
110				1	1			2	8			9	2	9	3	8
120			1				1			1		3	2	13	4	7
130	5	3	3	3			6	8	31	16	23	27	39	60	71	61
140															1	
150	1	1	1				3	2		1	5	13	17	9	29	30
160		2	1		1	1		1	2			10	2	12	12	6
170							1			2			1		1	1
180		1			1		1	3	3	1	9	6	9	18	26	22
190													1			2
200						3	1					2	3	2	14	2
210								1	1	1		4	2		2	15
220			1										1	1	1	3
230		1										2		2	5	3
240															1	1
250											2			1	6	1
260														1		1
270																
280															2	1
290															1	
300																
310																4

summaries of the Office of Climatology from 1941 to 1956 was reviewed and, *on the basis of the information available to the Office of Climatology and listed in these reports*, each of these tornadoes was then assigned a numerical rating. The results are shown in a frequency table as given in table 2.

The first thing that we notice as our eyes wander from left to right, across each one of the horizontal rows, is that the numbers tend in general to increase, perhaps a little more so after the period of 1948 and 1949, than previously. This reflects what we have already seen, namely, that the number of reports has increased during this period. However, there is another feature that is significant, and that is that the limit of the maximum rating per year seems to have a negative slope. This means that the *quality* of the details of the reports has also increased; that is, that we are receiving now more information in the reports than we have had in previous years. And finally, if we look at the numbers themselves we find that there have been marked increases in particular categories—in 0, 30, and 100. It is of interest to keep in mind that certain kinds of reports contribute in a major way to each of these categories, as follows:

1. The contributor to the 0 category is, of course, the report wherein none of the tornado rating elements has been included.
2. The primary contributor to the 30 category is the report of a storm with narrow path width (less than or equal to a quarter of a mile) but with no other rating element present.
3. The primary contributor to the 100 category is the report that a tornado has been observed but with no supporting evidence of any kind.

The conclusion is drawn that these types of reports have been included in increasing numbers in recent years because of the increased interest in the tornado problem; but *in all probability they were not part of the tornado statistics of previous years.* It is reasonable that in previous years, if a storm occurred with a narrow path, or if a funnel was reported to have been observed the storm would not have been classified as a tornado unless there was other evidence to substantiate a tornado classification.

A similar rating was made for all the other storms listed in the monthly summaries of the Office of Climatology, and table 3 gives the distribution for hail storms and other storms.

Here we see that, by far, most of the reports fall in a category of less than 50, very few between 50 and 100, and a negligible number over 100. For 1955 and 1956,

TABLE 3.—*Number of hail and other storm reports in severe local storm rating groups, 1955–56*

Rating	Hail		Other storms	
	1955	1956	1955	1956
0	488	161	253	677
10				
20			5	7
30	13	1	8	7
40				
50	17	1	13	32
60				
70				2
80			2	3
90				
100	1			2
110				
120				
130				1
140				
150				
160				
170				
180				
190				
200				
210				
220				1

therefore, the rating of less than or equal to 100 seems to include practically all of the reports of general storms, while practically no general storm ever is rated above 100.

Let us return to table 2. We repeat that it is our conclusion that:

1. tornadoes have not necessarily increased during the past 8 or 10 years;
2. an additional number of storms have been reported as tornadoes; and
3. these additional storms were essentially in the categories of 0, 30, and 100.

Figuratively speaking, it would seem that tornado reports since 1948 and 1949 have been "descending" in this distribution so that their numerical ratings have been increasing, while additional reports not given in previous years have been "poured on top". This suggests that we might, in a way, compare tornadoes with high ratings in recent years with tornadoes with lower ratings in the earlier years. On the other hand, the tornadoes with lower ratings in recent years were probably not reported as tornadoes in the early years. With this as an hypothesis, we counted upwards, starting from the bottom of each column, until we reached a total of in the vicinity of 150, the number which is comparable with the annual mean of all previous tornadoes, and the heavy line drawn on the table indicates where this cut-off is. We note that:

1. in 1955 and 1956 in accordance with what was stated earlier we eliminate all tornado reports equal to or less than 100,
2. the heavy line also has a negative slope comparable to the limit of the maximum numerical rating alluded to before, and
3. in certain cases the heavy line has to pass through a figure since taking it one side or the other would yield an annual number which would be out of line with the distribution of tornado reports in previous years.

The hypothesis, therefore, is that all the reports listed *below* the heavy line for all years are of comparable storms and their totals are comparable for the year. The reports *above* the heavy line are the additional reports that have been included in the statistics due to the increased interest and the increased activity in the tornado problem in recent years.

4. ADJUSTED TORNADO STATISTICS (1949–1956)

If we use only the reports below the heavy line and refer back to the curve of 5-year running means (fig. 2) we see that the adjusted values given in the dashed line represent quite well a continuation of events of previous years. Although based on justifiable deduction, this might seem somewhat artificial since, presumably, any grouping of numbers with values within the range of the previous 1916 to 1950 mean would provide a similar, nice, smooth 5-year curve. However, there is some additional evidence to substantiate this cutting off at the heavy line as given in table 2. This evidence is given in figure 4.

In figure 4 we have the monthly distribution of tornado reports from 1916 to 1950. The range for each month is given by the upright vertical line, on which are represented the upper and lower quartiles and the mean. The tornado reports listed below the heavy line in table 2 were reviewed and tabulated according to their monthly occurrence. If indeed these reports are comparable and compatible with the tornado reports from 1916 to 1950, they should be revealed as part of the same population, namely, they should fall within the general range and means of previous statistics for previous years. This figure shows that they do, indeed. The small numbers, from 0 to 6, represent the years of the 1950 decade—that is, 0 stands for 1950, 1 for 1951, etc. The numbers that have the dot next to them represent the upper and lower limits for that month for that year. In three years, 1950, 1953, and 1954, two limits were required because the heavy line in table 2 had to cut through certain numbers and one could not tell which report to omit and which one not to omit. It can be seen from this frequency distribution that the reports that have been used do indeed appear as if they were part of the population of all previous reports for the months from 1916 to 1950.

In this manner we are able to make the statistics for tornadoes during the past 8 or 10 years compatible with the tornado reports of previous years.

5. CLASSIFICATION OF TORNADO REPORTS

We next ask ourselves if we can utilize the analysis which we have just gone through in future tornado classification. Table 4 is a recommended classification. Utilizing the numerical ratings as given in table 1, the details of any report may be reviewed and a total rating assigned. The classification would then be as follows:

A. All tornado reports whose total numerical rating is greater than 100, shall be classified as *tornado*. (The five items listed under this group in table 4 represent the various combinations that may yield this type of report. The letters refer to the items in table 1. For example: "1. a+ . . . " means that a tornado report will be classified as a tornado if a funnel was observed *and* if any one other of the items below is also reported. This would give a number greater

TABLE 4.—*Recommended classification of tornado reports. Numbers refer to total ratings as assigned to report (table 1) and letters to the specific rating items of table 1*

A. >100 (Tornado) 1. a+ . . . 2. 2b+ . . . 3. b+2c 4. b+c+2d 5. 3c+d	C. 30-70 (Severe local storm) 1. b 2. 2c 3. c+d 4. c 5. 2d 6. c+2d
B. 80-100 (Possible tornado) 1. a 2. 2b 3. b+c 4. b+c+d 5. b+2d 6. 3c 7. 2c+2d 8. 2c+d	D. 0–20 (Local storm) 1. d 2. -

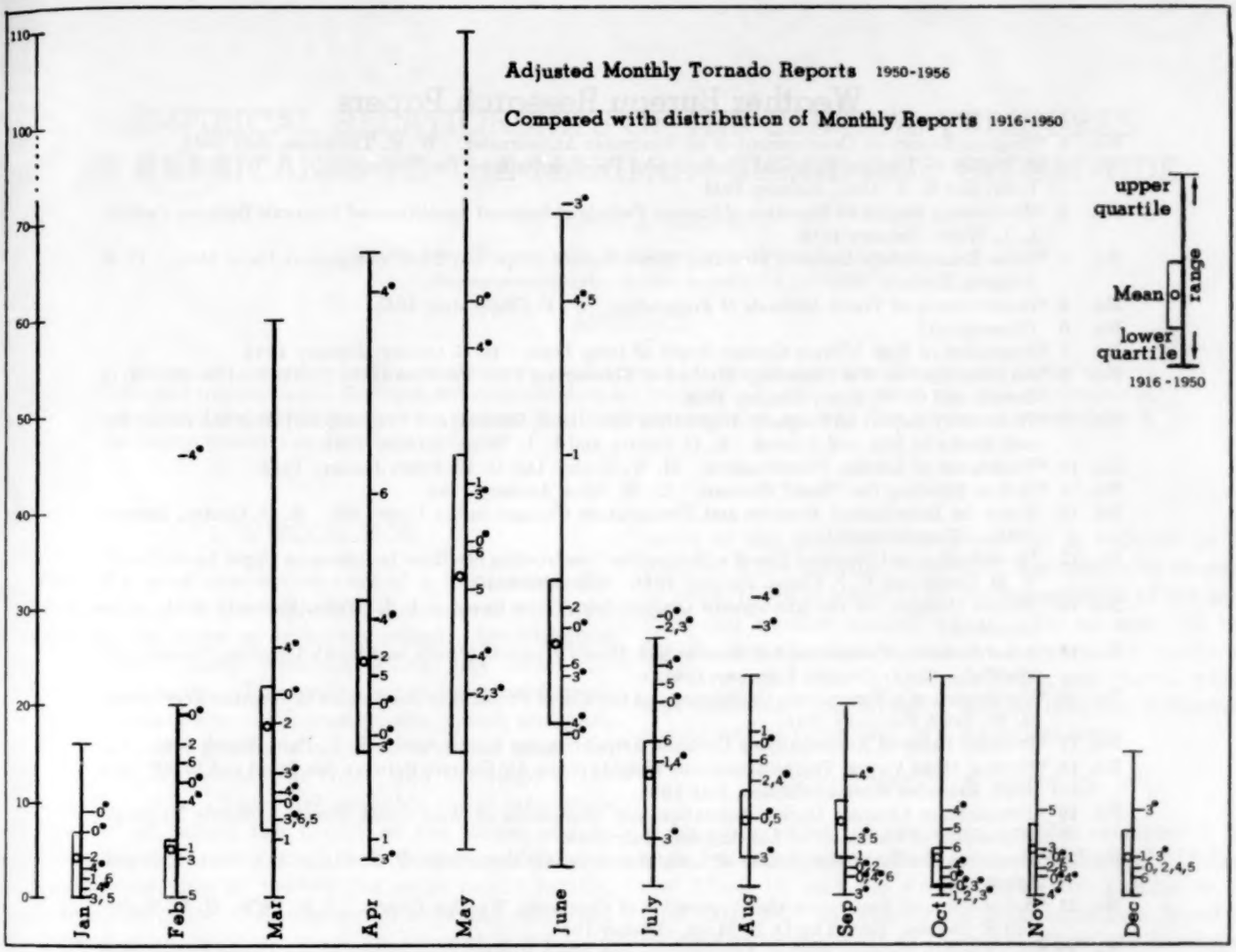

FIGURE 4.—Adjusted monthly tornado reports 1950–1956 compared with distribution of monthly reports 1916–1950. Range, upper quartile, lower quartile, and mean of monthly tornado reports 1916–1950 are given in diagram to right. Numerals refer to year of 1950 decade. Small dots indicate that two values appear for that year showing upper and lower limit.

than 100. "5. 3c+d" means that all three items under c.—explosive-type damage, narrow path, and skipping action—were reported plus one of d., twisting-type damage, or the lifting of objects.)

B. A total rating between 80 and 100 inclusive shall be that of a *possible tornado*. Again the various possible combinations are listed.

C. A total rating between 30 and 70 inclusive shall be that of a *severe local storm*.

D. Finally, those that do not have a rating of more than 20—that is 0 and 20—shall be classified only as a *local storm*.

6. SUMMARY

The classification as given in table 4 and the ratings in table 1 should not be considered inflexible but only as a point of departure; i. e., they are but a first attempt to give numerical ratings to the various items in reports that seem to be significant and then to group the ratings objectively as to a *tornado, possible tornado, severe local storm*, or *local storm*. This scheme may have many limitations. For example, it has a bias against nighttime tornadoes since there is less likelihood that a funnel can be observed at that time. On the other hand, one may well argue against calling a night storm anything more than a "possible tornado," if a funnel is not reported. With further thought put to this problem, this classification may have to be changed. It probably will be changed, but this seems to be a working tool with which to start.

ACKNOWLEDGMENTS

The author acknowledges the invaluable assistance offered to him by Messrs. W. A. Hass, J. Hand, and R. Brown and Mrs. A. Fuller of the Severe Local Storms Research Unit, in the collection and tabulation of the data used in this paper.

Weather Bureau Research Papers

No. 1 *Progress Report on Development of an Electronic Anemometer. W. R. Thickstun, July 1943.
No. 2 *A Project to Test the Potential Usefulness of Pressure Patterns for Forecasting. H. W. Norton, G. W. Brier, and R. A. Allen, January 1944.
No. 3 *Preliminary Report on Duration of Stormy Periods at Selected Localities and Intervals Between Periods. L. L. Weiss, January 1944.
No. 4 *Some Relationships Between Five-Day Mean Surface Maps and Their Component Daily Maps. C. B. Johnson, January 1944.
No. 5 *Improvement of Trend Methods of Forecasting. P. F. Clapp, July 1943.
No. 6 (Unassigned.)
No. 7 *Formation of New Moving Centers South of Deep Lows. R. C. Gentry, January 1944.
No. 8 *An Investigation of a Trajectory Method of Forecasting Flow Patterns at the 10,000-Foot Level. H. G. Dorsey and G. W. Brier, January 1944.
No. 9 *Preliminary Report on Stagnant Highs Over Greenland, Iceland, and England, and Over the Bering Sea and Alaska in July and August. R. C. Gentry and L. L. Weiss, January 1944.
No. 10 *Persistence in London Temperatures. H. W. Norton and G. W. Brier, January 1944.
No. 11 *Skill in Selecting the "Best" Forecast. G. W. Brier, January 1944.
No. 12 Notes on Interdiurnal Pressure and Temperature Changes in the Upper Air. R. C. Gentry, January 1944. (Unpublished.)
No. 13 Investigation and Practical Use of a Method for Constructing Six-Hour Isallobars on Upper Level Charts. E. M. Cason and P. F. Clapp, January 1944. (Unpublished.)
No. 14 Weight Changes for the Atmosphere Divided Into Three Layers. L. L. Weiss, February 1944. (Unpublished.)
No. 15 *Some Notes on Forecasting for Atlanta and Miami Districts (North and South Carolina, Georgia, and Florida). Grady Norton, February 1944.
No. 16 *Verification of a Forecaster's Confidence and the Use of Probability Statements in Weather Forecasting. G. W. Brier, February 1944.
No. 17 *Pressure Patterns Accompanying Cyclonic Activity in the Azores Area. R. L. Pyle, March 1944.
No. 18 *Normal Mean Virtual Temperatures and Weights of the Air Column Between Sea Level and 10,000 Feet. Staff, Extended Forecast Section, July 1944.
No. 19 *Temperature Changes During Formation and Dissipation of West Coast Stratus. Morris Neiburger (University of California at Los Angeles), July 1944.
No. 20 Empirical Studies of the Motion of Long Waves in the Westerlies. P. F. Clapp, July 1944. (Unpublished.)
No. 21 *A Collection of Reports on the Preparation of Prognostic Weather Charts. J. R. Fulks, H. B. Wobus, and S. Teweles, Edited by C. P. Mook, October 1944.
No. 22 *Relationship Between Surface Temperature and Mean Virtual Temperature in the Lower Troposphere. W. M. Rowe, November 1944.
No. 23 *Forecasting the Time of Formation of Stratus Cloud Ceiling at Oakland, California, Airport. Edward M. Vernon, April 1945.
No. 24 *Investigation of Polar Anticyclogenesis and Associated Variations of the Zonal Index. Jerome Namias, September 1945.
No. 25 *Progress Report on Objective Rainfall Forecasting Research Program for the Los Angeles Area. J. C. Thompson, July 1946.
No. 26 *A Study of Quantitative Precipitation Forecasting in the TVA Basin. Glenn W. Brier, November 1946.
No. 27 *Objective Methods of Forecasting Winter Minimum Temperatures at Washington, D. C. C. P. Mook and Saul Price, August 1947.
No. 28 *Possibility of Long Range Precipitation Forecasting for the Hawaiian Islands. Samuel B. Solot, January 1948.
No. 29 An Objective Method of Forecasting Five-Day Precipitation for the Tennessee Valley. William H. Klein, July 1948. .30
No. 30 First Partial Report on the Artificial Production of Precipitation: Stratiform Clouds—Ohio, 1948. Richard D. Coons, R. C. Gentry, and Ross Gunn, August 1948. .30
No. 31 Second Partial Report on the Artificial Production of Precipitation: Cumuliform Clouds—Ohio, 1948. Richard D. Coons, Earl L. Jones, and Ross Gunn, January 1949. .30
No. 32 Further Studies in Hawaiian Precipitation. Samuel B. Solot, January 1950. .30

*Out of print.

NOTE.—Nos. 2, 3, 4, 7, 8, 9, 10, and 11 are included in one publication under the title "A Collection of Reports on Extended Forecasting Research." Weather Bureau, 1944.

(*Continued on p. 192*)

EMPIRICAL RELATIONSHIPS OF THE CENTRAL PRESSURES IN HURRICANES TO THE MAXIMUM SURGE AND STORM TIDE

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ABSTRACT

Surge and storm tide profiles are constructed to determine the maximum surge and storm tide heights of hurricanes and tropical storms for which sufficient tide data are available. In cases where less tide data are obtainable, interpolated and extrapolated profiles are used to estimate the maximum heights. The relation of these heights to the central pressures of the storms is shown.

1. INTRODUCTION

Often the most destructive part of a hurricane is the hurricane surge, or the rapid rise in sea level which accompanies the storm as it moves inland. Investigators have suggested many variables which may affect the height of this surge. To mention a few, we would speak of such parameters as the intensity, size, speed, and path of the storm; the general configuration of the coastline; bottom topography near the coast; and the stage of the astronomical tide. There are probably other large-scale features which affect the height of the surge, and in addition, there are many small-scale features which may, in many cases, greatly modify the surge height locally, such as convergence or divergence in bays and estuaries, local wind-setup, seiching, etc. An attempt is made in this study to develop a forecasting tool which embodies some of the broadscale features and minimizes the local effects.

A moderately large number of tide observations is available for a few hurricanes, but for the majority of the storms there are only a few good observations and often none within the zone of hurricane winds. Conner, Kraft, and Harris [1] have recently published a paper in which the highest observed storm tide along the open coast is related to the lowest central pressure in the storm. This procedure is biased in the direction of underestimating the maximum tide height, for the highest actual tide may frequently go unobserved. This is especially true when no observations are obtained near the center of the storm.

There is some hope of correcting this defect and increasing the number of storms used in the formation of the prediction equation by constructing standard tide profiles which could be used for estimating the maximum storm tide from the observed high tides of a large number of storms. This procedure involves the acceptance of certain assumptions, which further study may show to be unjustified, but in view of the limited amount of first class data available at the present time, and the importance of the problem, this procedure is believed to be justified if not actually required. A considerable amount of subjectivity is required in the construction of the profiles, and another analyst might differ on many of the details, but the close agreement between the results of this study and that by Conner, Kraft, and Harris, which was conducted concurrently, implies that the differences should not be significant in a statistical sense.

2. INDIVIDUAL TIDE PROFILES

An examination of the surge profiles constructed by such investigators as Redfield and Miller [2], Hubert and Clark [3] and the writer, shows the profiles to be "bell shaped". In general, the peaks have been found to be near or to the right of the point where the hurricane enters the coastline. Barring some abnormality in the coastline, it is logical to believe that there is one place where the surge is higher than at surrounding points and that the surge height decreases with distance from this point. With this in mind, surge profiles have been drawn of cases for which sufficient tide data were available.

Figure 1 contains examples of two tide profiles (see appendix for balance of the profiles used in this study). These two profiles are neither the poorest nor the best documented ones used in the study; they are presented to show the manner in which they are drawn and the subjectivity involved.

The basic assumption in studies of this type is that the storm surge, that is, the difference between the actual elevation of the sea surface and the elevation which would have existed in the absence of a storm, is strongly related to the minimum atmospheric pressure in the storm. A continuous record of the water elevation and a continuous prediction of the normal tide are obviously necessary to permit an accurate determination of the storm surge. Data of this type have been used where available, and are indicated by solid circles on the profile charts. However, many good observations of the maximum tide

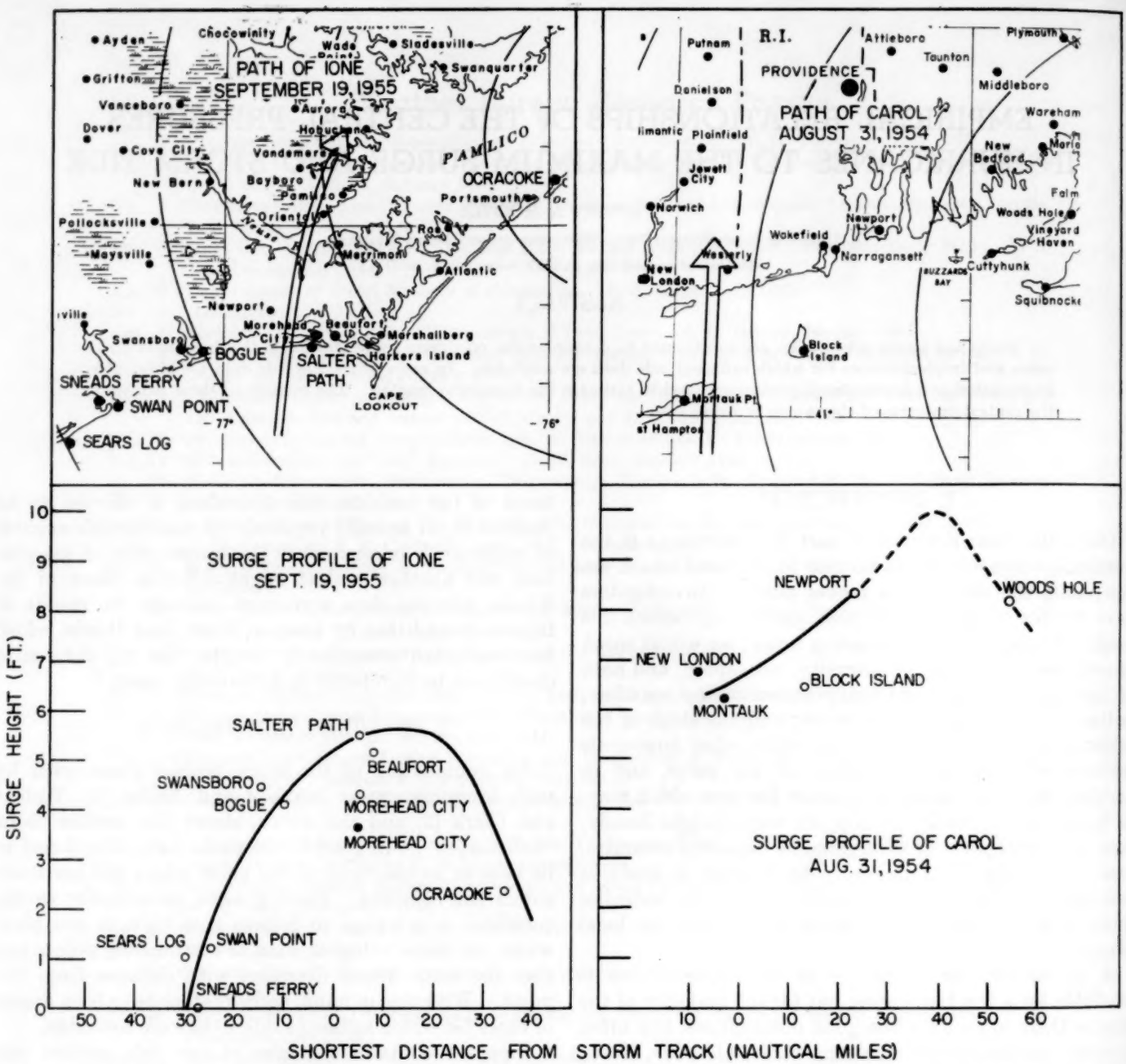


FIGURE 1.—Surge profiles of hurricanes Ione, September 19, 1955 and Carol, August 31, 1954. Open circles indicate discontinuous-type data.

height are obtained from locations which do not have recording tide gages, and in some cases the recording tide gages have failed before the highest tide elevations were reached. In such cases the maximum height of the observed tide and its time of occurrence may be known, and a good estimation of the stage of the astronomical tide at this time may be available, yet this is not sufficient for an accurate determination of the maximum storm surge unless the highest meteorologic tide coincides with the time of predicted high tide. The reason for this can be readily seen by reference to figure 2 which shows the observed, predicted, and meteorologic tides at the Little Creek gage, Norfolk, Va., for hurricane Connie. Note that the maximum observed tide occurred near the time of a predicted high tide and yielded a surge value of 2.3 feet, while the maximum surge of 4.2 feet occurred near the time of predicted low tide. Due to the very limited amount of ideal data for this study, data of the discontinuous type must be used and have been indicated on the figures by open circles. In these instances an estimate of the stage of the astronomical tide was made and removed from the observed tide by assuming the maximum surge height to have occurred near the time the storm entered the coast.

Most of the continuously recorded water level data used in this study have been obtained from the U. S.

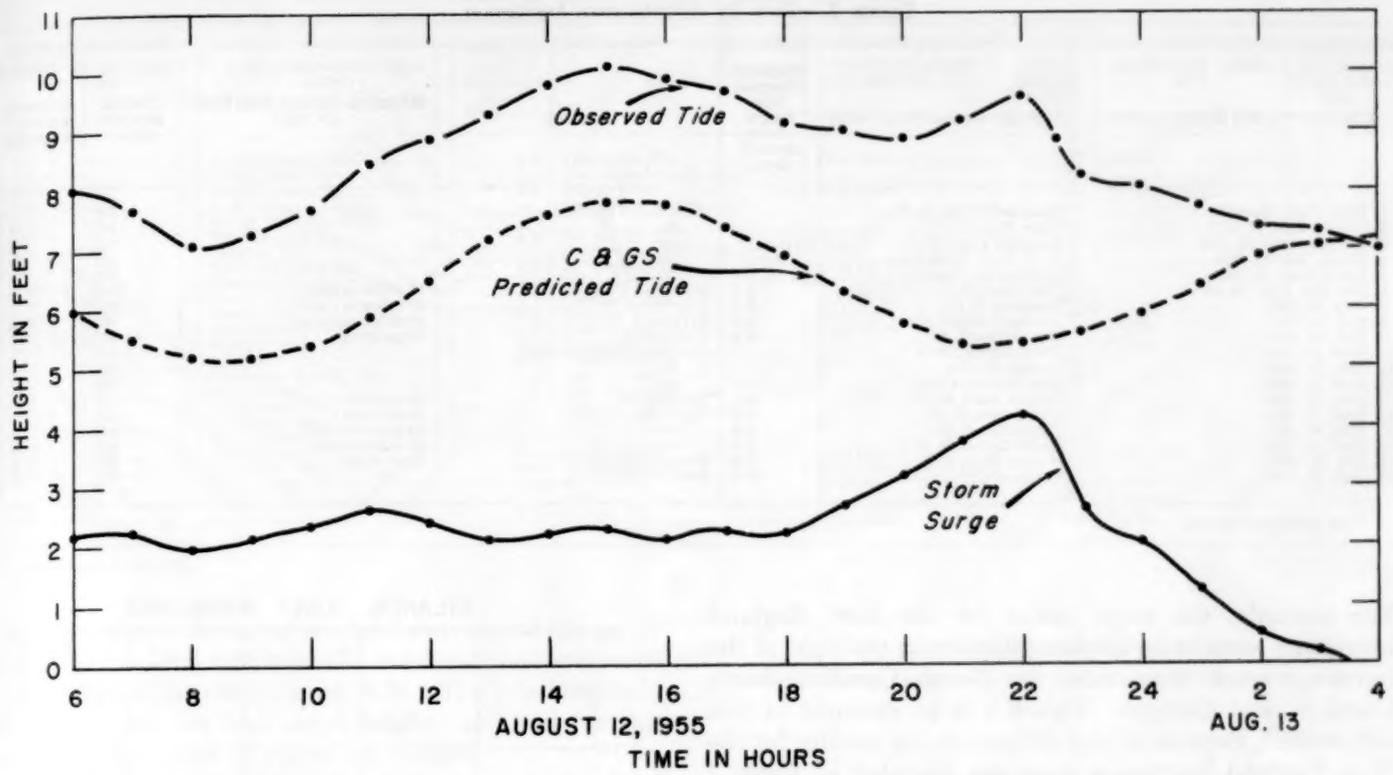


FIGURE 2.—Observed, predicted, and meteorologic tides at Little Creek, Norfolk, Va., for hurricane Connie, August 1955.

Coast and Geodetic Survey. Local observations of maximum tide height have been obtained from many sources, but most of the data not previously published have been furnished by the District Offices of the U. S. Army Corps of Engineers.

The profiles were drawn by inspection with some consideration being given to how nearly the observations were believed to represent open coast conditions. For example, in the case of Ione, shown in figure 1, the two Morehead City values were given less weight than the Salter Path value which was believed to be more representative.

In the case of Carol, the data for Newport and Woods Hole, although obtained from tide gage locations, are shown as open circles because both these gages became inoperative before the highest water levels were reached in this storm. The Coast and Geodetic Survey observations are more or less drawn for, while the estimated value at Block Island is given less weight. Tide observations for other hurricanes at Block Island have been found to be lower than those along the southern New England coast. Perhaps this is because the surge has the opportunity to pass by Block Island, while the southern coast of New England forms more of a barrier. The peak is shown as 10 feet, but, admittedly in this case, the profile could have been drawn to show a peak anywhere between 9 and 11 feet.

3. INTERPOLATED PROFILES

It was found that tide profiles for certain coastlines resemble one another more than those for other coastlines.

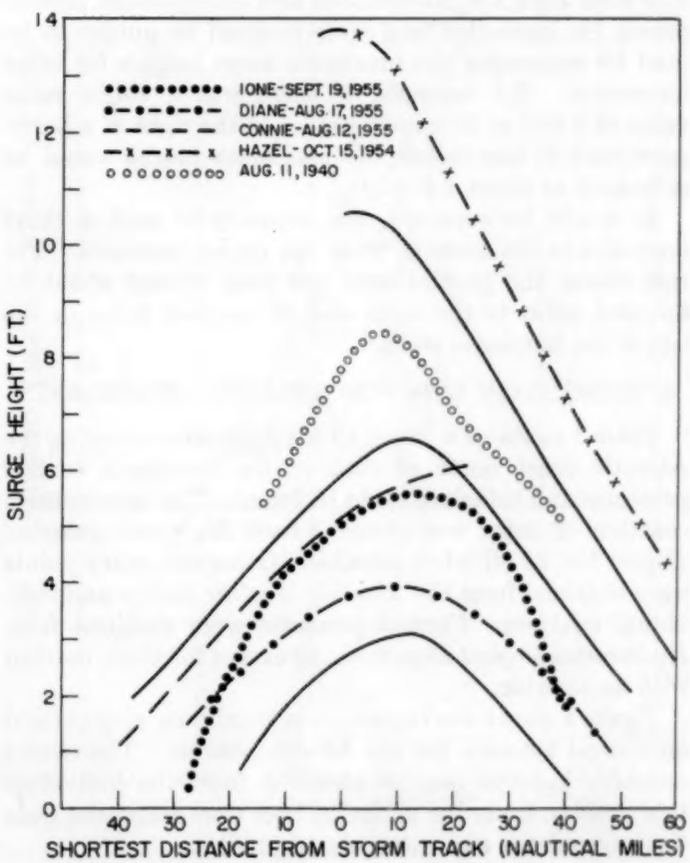


FIGURE 3.—Surge profiles of the hurricanes which entered the coasts of North Carolina, South Carolina, and Georgia.

TABLE 1.—*Data for Atlantic coast hurricanes*

Reference No. and date of hurricane	Approximate coastline of entry	Maximum observed tide height above normal (feet)	Location	Minimum distance from track (N. mi.)	Central pressure (mb.)	Estimated maximum surge (ft.)
1. Ione, Sept. 19, 1955	Morehead City, N. C		(Individual profile used)		966	5.7
2. Diane, Aug. 17, 1955	Cape Fear, N. C		do		987	3.9
3. Connie, Aug. 12, 1955	Beaufort Inlet, N. C		do		968	6.0
4. Hazel, Oct. 15, 1954	N. C.-S. C. State Line		do		937	13.8
5. Carol, Aug. 31, 1954	Stonington, Conn		do		962	9.9
6. Barbara, Aug. 13, 1953	Wildwood, N. C	1.5	Morehead City, N. C	10 miles to left	*989	2.4
7. Aug. 30, 1952	Beaufort, S. C	3.2	Charleston, S. C	40 miles to right	983	5.5
8. Oct. 15, 1947	Ossabaw Sound, Ga	8.5	Savannah, Ga	10 miles to right	968	8.7
9. Oct. 19, 1944	Charleston, S. C	4.3	Charleston, S. C	Near track	*980	5.0
10. Sept. 14, 1944	Point Judith, R. I		(Individual profile used)		959	8.9
11. Aug. 11, 1940	Savannah, Ga		do		975	8.3
12. Sept. 21, 1938	New Haven, Conn		do		948	11.6
13. Aug. 23, 1933	Oregon Inlet, N. C	6.7	Norfolk, Va	10 miles to right	970	6.9
14. Sept. 18, 1928	Charleston, S. C	3.8	Charleston, S. C	Near track	*979	4.2
15. Aug. 28, 1911	Hilton Head, S. C	5.6	do	30 miles to right	979	8.0
16. Sept. 17, 1906	Cedar Island, S. C	1.5	do	30 miles to left	981	3.0
17. Oct. 13, 1893	Winyah Bay, S. C	8.3	Winyah Bay, S. C	Near track	959	8.6
18. Aug. 28, 1893	Savannah, Ga	15.3	Fort Pulaski, Ga	do	*950	15.5

*Not obtained from [4].

For example, the surge peaks for the New England hurricanes seem to be displaced farther to the right of the hurricane track than those for North Carolina, South Carolina, and Georgia. Figure 1 is an example of this difference. Because of this difference, the profiles for the New England hurricanes were not included in figure 3 which contains the profiles for hurricanes entering the coasts of North Carolina, South Carolina, and Georgia. The solid lines are interpolated and extrapolated profiles drawn by inspection and were inserted as guides to be used for estimating the maximum surge heights for other hurricanes. For example, if there was a single surge value of 5 feet at 30 nautical miles to the right of a hurricane track in this region, the maximum height would be estimated as about 7 feet.

As would be expected, the accuracy of such a chart decreases as the distance from the center increases. For this reason the profiles were not used beyond about 50 nautical miles to the right and 40 nautical miles to the left of the hurricane track.

4. REGRESSION LINE FOR ATLANTIC HURRICANES

Table 1 contains a list of all the hurricanes entering the Atlantic coast north of Jacksonville for which central pressures and tide data could be found. The approximate coastline of entry was obtained from *Hydrometeorological Report No. 32* [4] when possible. Otherwise entry points were obtained from the *Monthly Weather Review* and individual analyses. Central pressures were obtained from *Hydrometeorological Report No. 32* except for those marked with an asterisk.

Figure 4 shows the regression of maximum surge height on central pressure for the Atlantic storms. The circled numbers indicate heights obtained from the individual tide profiles, while the uncircled ones were estimated from the interpolated and extrapolated profiles.

5. GULF OF MEXICO HURRICANES

Because most of the available tide values for the Gulf

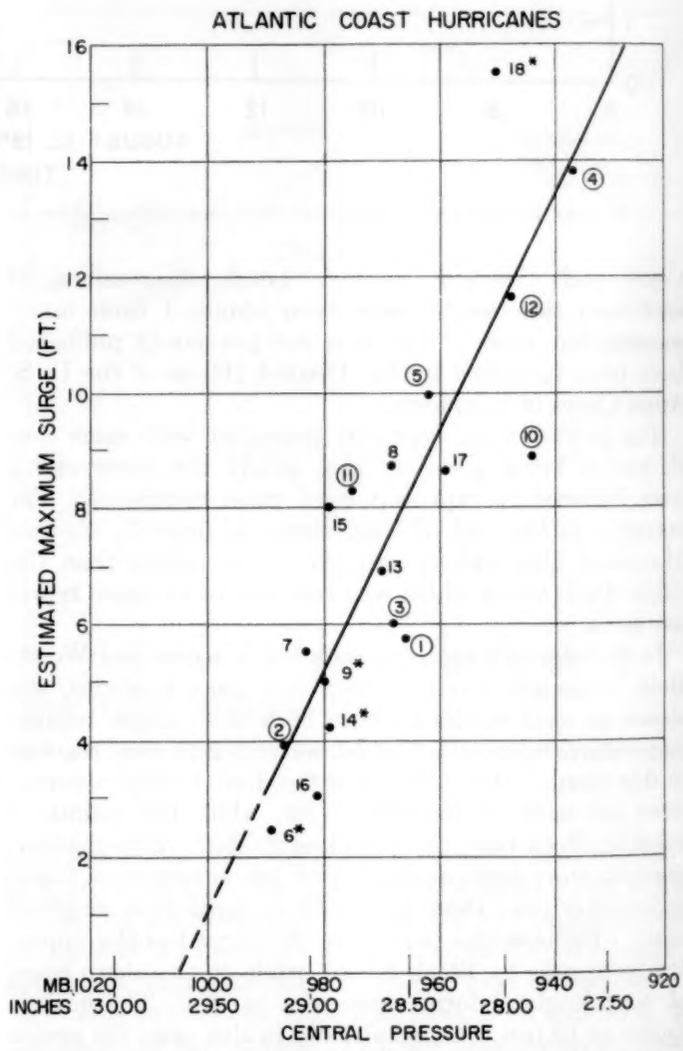


FIGURE 4.—Regression of maximum surge height on central pressure for hurricanes entering the United States Atlantic coastline north of Jacksonville, Fla. Plotted numbers correspond to storm numbers in table 1; those circled are obtained from individual tide profiles, others are extrapolated or interpolated. Asterisk indicates central pressure not obtained from [4]. NOTE: Point 10 is misplotted; it should be at a pressure of 959 mb.

TABLE 2.—*Data for Gulf of Mexico hurricanes*

Reference No. and date of hurricane	Approximate coast line of entry	Maximum observed tide height above MSL (ft.)	Location	Minimum distance from track (N. mi.)	Central pressure (mb.)	Interpolated profiles used	Estimated maximum storm tide (ft.)
1. Aug. 30, 1950	Orange Beach, Ala	5.5	Pensacola, Fla	15 to right	979	South	5.8
2. Oct. 4, 1949	Cedar Lake, Tex		(Individual profile used)		978		10.4
3. Sept. 4, 1948	Grand Island, La	5.6	Biloxi, Miss	45 to right	*987	South	10.0
4. Sept. 19, 1947	New Orleans, La		(Individual profile used)		968		13.0
5. Aug. 27, 1945	Matagorda Island, Tex		do		968		8.7
6. July 27, 1943	Port Bolivar, Tex	4.0	Galveston, Tex	10 to left	975	Southeast	10.0
7. Aug. 30, 1942	Seadrift, Tex		(Individual profile used)		951		14.0
8. Oct. 7, 1941	Harbeson City, Fla	8.0	St. Marks, Fla	25 to right	981	Southeast	8.0
9. Sept. 23, 1941	5 miles SW Sargent, Tex	9.9	Sargent, Tex	5 to right	959	do	12.3
10. Aug. 7, 1940	Texas Point, La	4.8	Calcasieu Pass, La	20 to right	974	do	5.0
11. July 31, 1936	Destin, Fla	6.0	Panama City, Fla	40 to right	964	do	7.0
12. Sept. 5, 1933	Brownsville, Tex	13.0	Brownsville, Tex	Near track	949	do	14.8
13. Sept. 20, 1926	Perdido Bay, Ala	7.6	Pensacola, Fla	7 to right	956	do	11.4
14. Aug. 25, 1926	Lake Pelt, La	10.0	Timbalier Bay, La	30 to right	959	do	10.3
15. Sept. 14, 1919	Chapman Ranch, Tex	11.1	Port Aransas, Tex	30 to right	948	do	11.3
16. Sept. 28, 1917	Horosa, Fla	7.1	Fort Barrancas, Fla	10 to left	964	South	9.6
17. July 5, 1916	Pascagoula, Miss		(Individual profile used)		961		8.1
18. Sept. 29, 1915	Timbalier Pass, La		do		944		11.2
19. Aug. 16, 1915	Freeport, Tex		do		953		14.8
20. Sept. 13, 1912	Cedar Point, La	4.4	Mobile, Ala	15 to right	*993	Southeast	5.0
21. July 21, 1909	4 miles SW Freeport, Tex	10.0	Galveston, Tex	35 to right	959	do	10.8
22. Aug. 14, 1901	Biloxi, Miss	7.4	Mobile, Ala	22 to right	973	South	9.0
23. Sept 8, 1900	6 miles NE Freeport, Tex	14.5	Galveston, Tex	25 to right	936	Southeast	15.0
24. Oct. 2, 1893	Mobile, Ala	8.4	Mobile, Ala	Near track	956	South	12.3

*Not obtained from [4].

coast were above the mean sea level datum and the range of the astronomical tide is small, no adjustment was made for the stage of the astronomical tide. The tide heights in these cases are not true surge heights and will for this reason be referred to as storm tide heights.

In this portion of the study extensive use was made of the profiles constructed by Hubert and Clark [3]. Some were used as they were drawn, while in other cases where new data and information were found, slight changes were made. Tide data supplied by Mr. James Taylor of Galveston was also used in the construction of these profiles. The same type of tide report designation used by Hubert and Clark was followed.

An examination of the individual profiles for the Gulf hurricanes seemed to indicate that profiles of hurricanes which entered the coastline from the east-southeast and southeast were broader than those entering the coastline from the south-southeast, south, or south-southwest. For this reason best results were obtained by dividing the profiles into these two groups. Interpolated and extrapolated profiles were drawn in the same fashion as those for the Atlantic coast. (See appendix for the Gulf coast profiles.)

The Florida Peninsula was not included in this study because it was felt that a separate set of profiles would be needed, and only one profile for each side of the Peninsula was available.

Table 2 contains a list of all the Gulf coast storms used in this study. All of the data contained in the column Maximum Observed Tide Height were obtained from Conner, Kraft, and Harris [1]. Four cases included in their paper were omitted because the tide observations were considered to be too distant from the storm track. These were the hurricanes of September 27, 1906, September 20, 1909, July 25, 1934, and August 24, 1947. In addition, storms entering the Florida Peninsula were not included for the reasons given above. These were the hurricanes of October 25, 1921 and September 5, 1950.

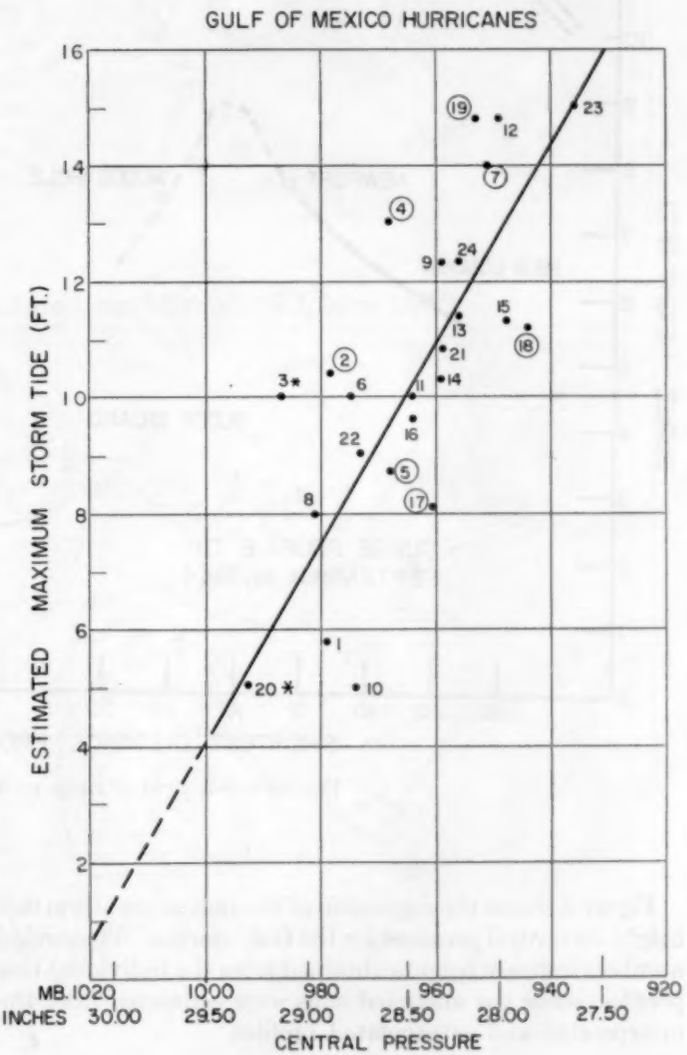


FIGURE 5.—Regression of maximum storm tide height on central pressure for hurricanes entering the United States Gulf of Mexico coastline west of Tallahassee, Fla.

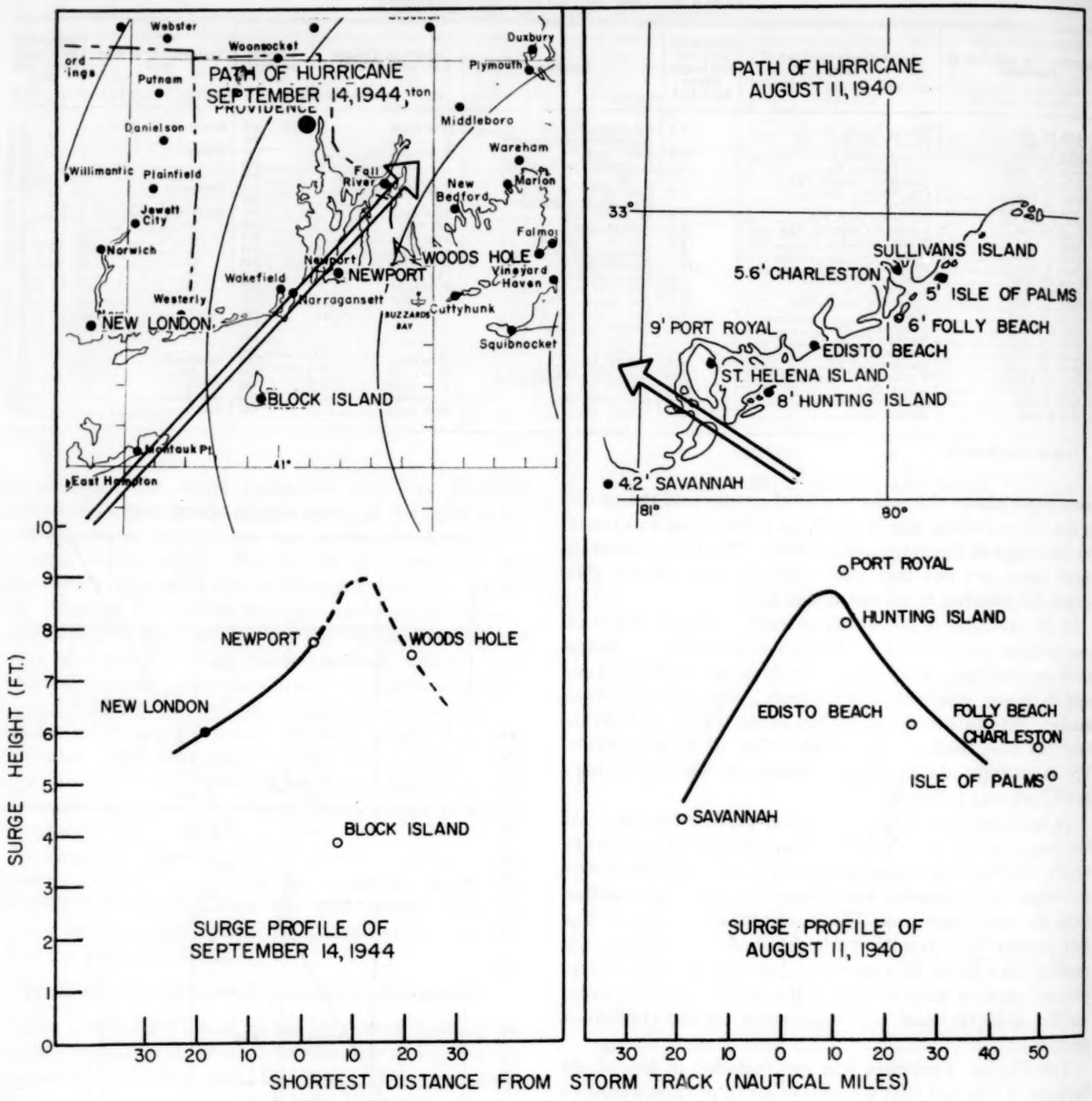


FIGURE 6.—Individual surge profiles for two Atlantic coast hurricanes.

Figure 5 shows the regression of the maximum storm tide height on central pressure for the Gulf storms. The circled numbers indicate heights obtained from the individual tide profiles, while the uncircled ones were estimated from the interpolated and extrapolated profiles.

6. DISCUSSION

The regression line obtained from this sample of Atlantic coast storms may be expressed as

$$h_{ext}=0.198(1006-p_o) \quad (1)$$

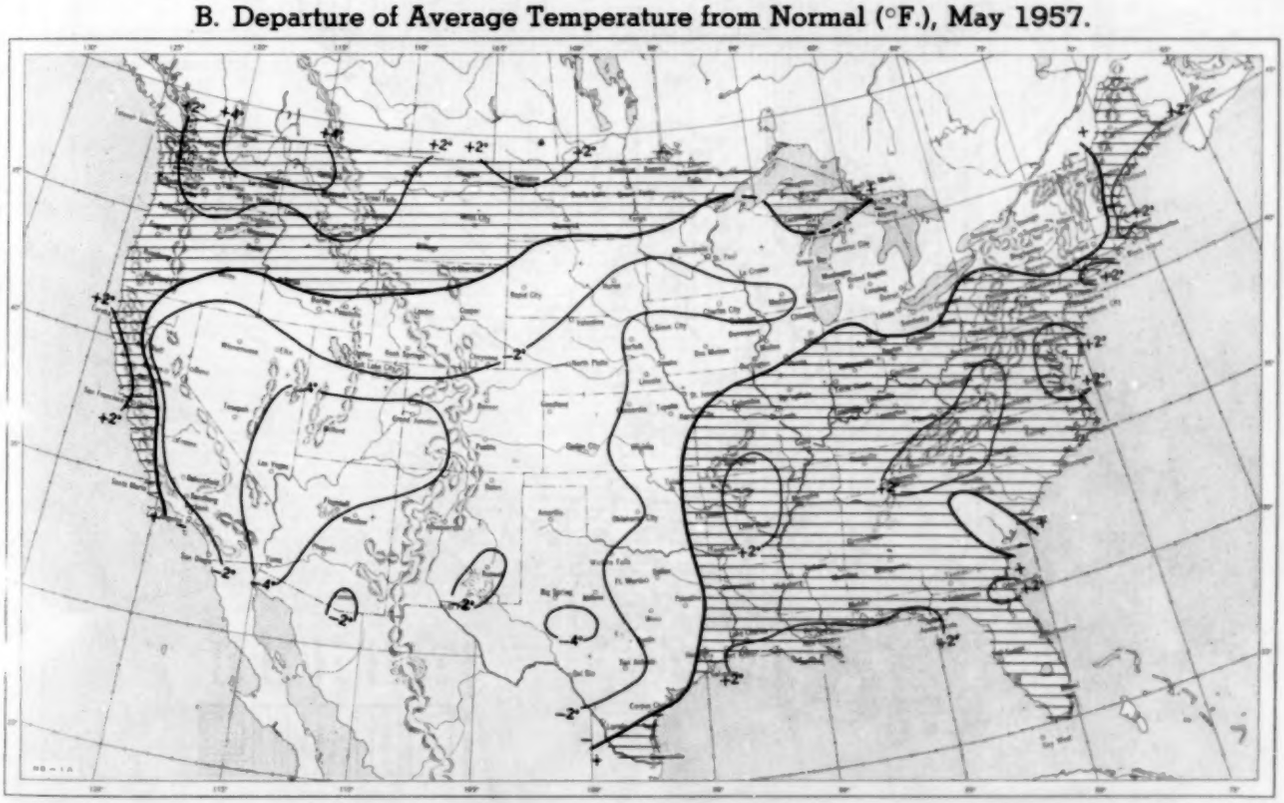
where p_o is the central pressure in millibars as the storm came inland and h_{ext} is the extreme storm surge in feet. The coefficient of correlation was found to be 0.86.

The regression line for the Gulf of Mexico coast storms was calculated to be

$$h_{ext}=0.151(1032-p_o) \quad (2)$$

Chart I. A. Average Temperature (°F.) at Surface, May 1957.

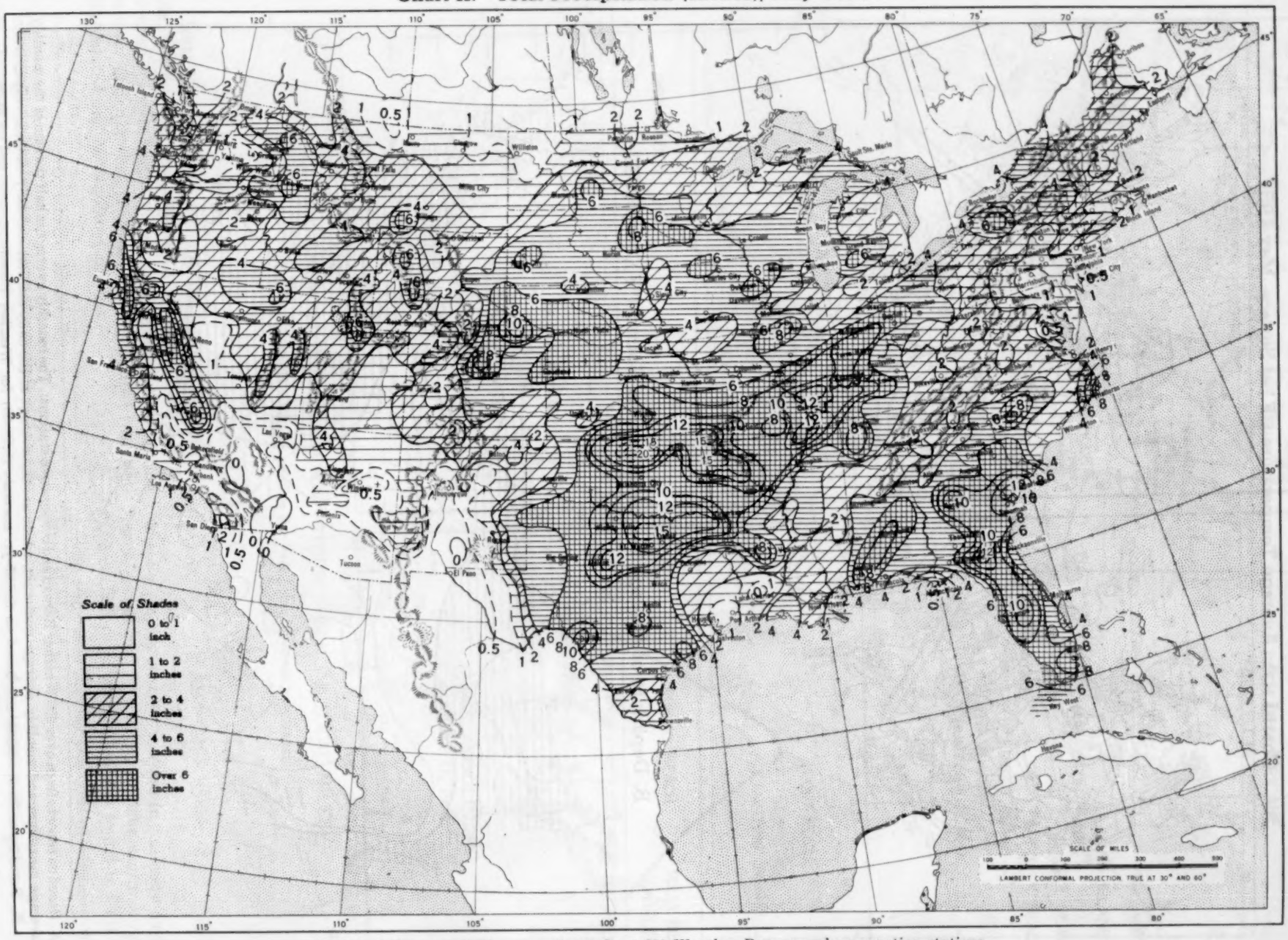
B. Departure of Average Temperature from Normal (°F.), May 1957.



A. Based on reports from over 900 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.

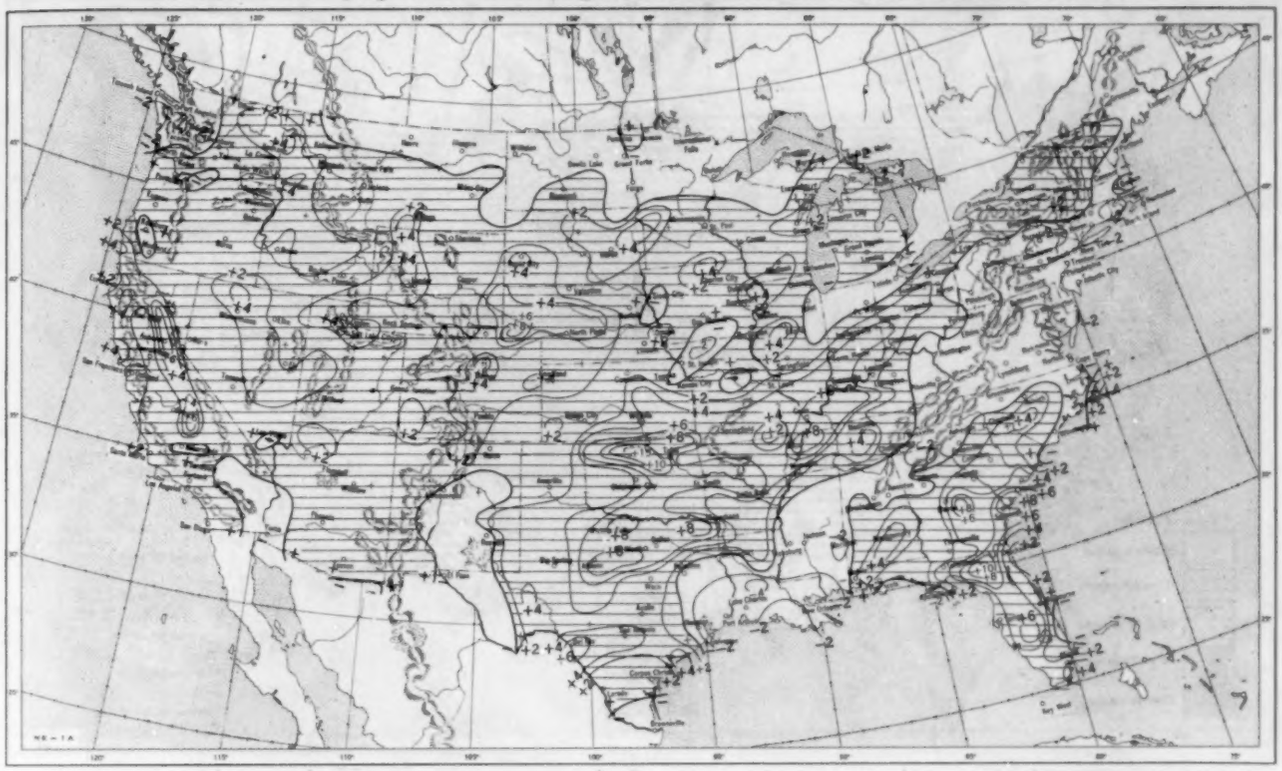
B. Departures from normal are based on the 30-yr. normals (1921-50) for Weather Bureau stations and on means of 25 years or more (mostly 1931-55) for cooperative stations.

Chart II. Total Precipitation (Inches), May 1957.

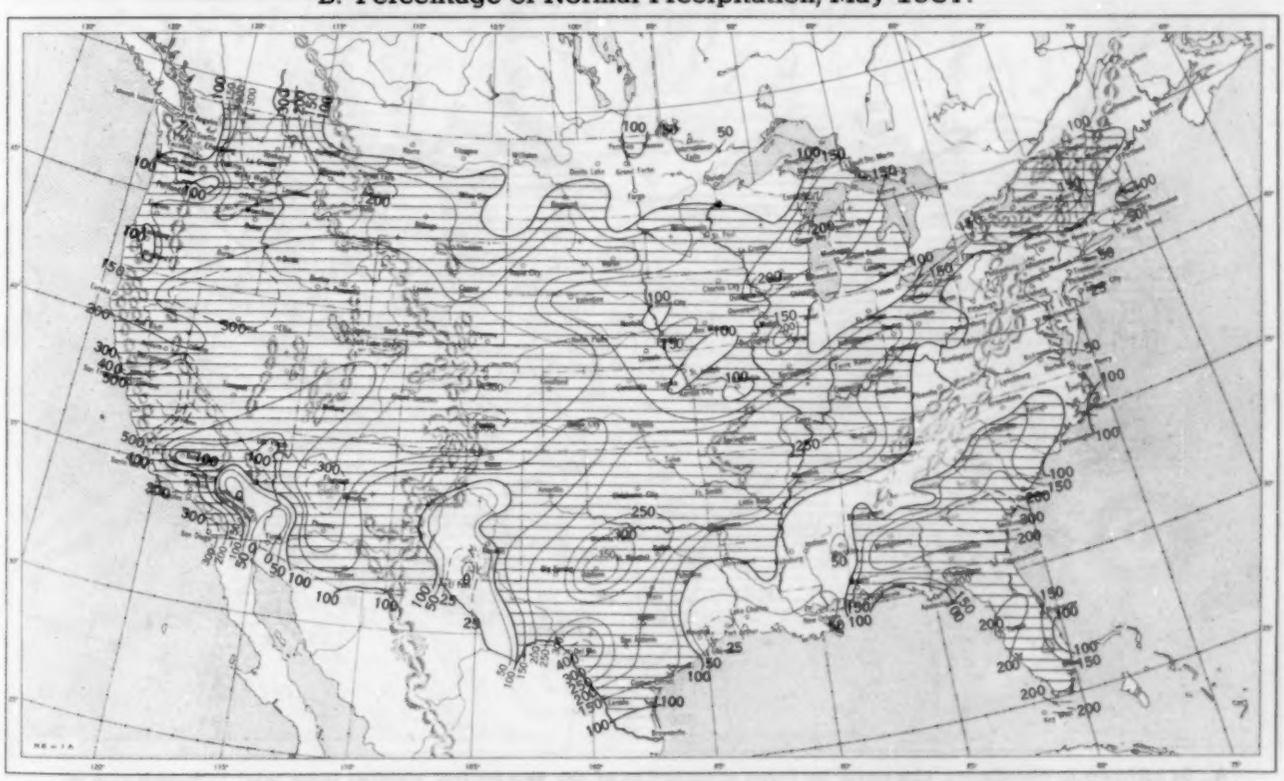

Scale of Shades
0 to 1 inch
1 to 2 inches
2 to 4 inches
4 to 6 inches
Over 6 inches
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION TRUE AT 30° AND 60°

Based on daily precipitation records at about 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), May 1957.

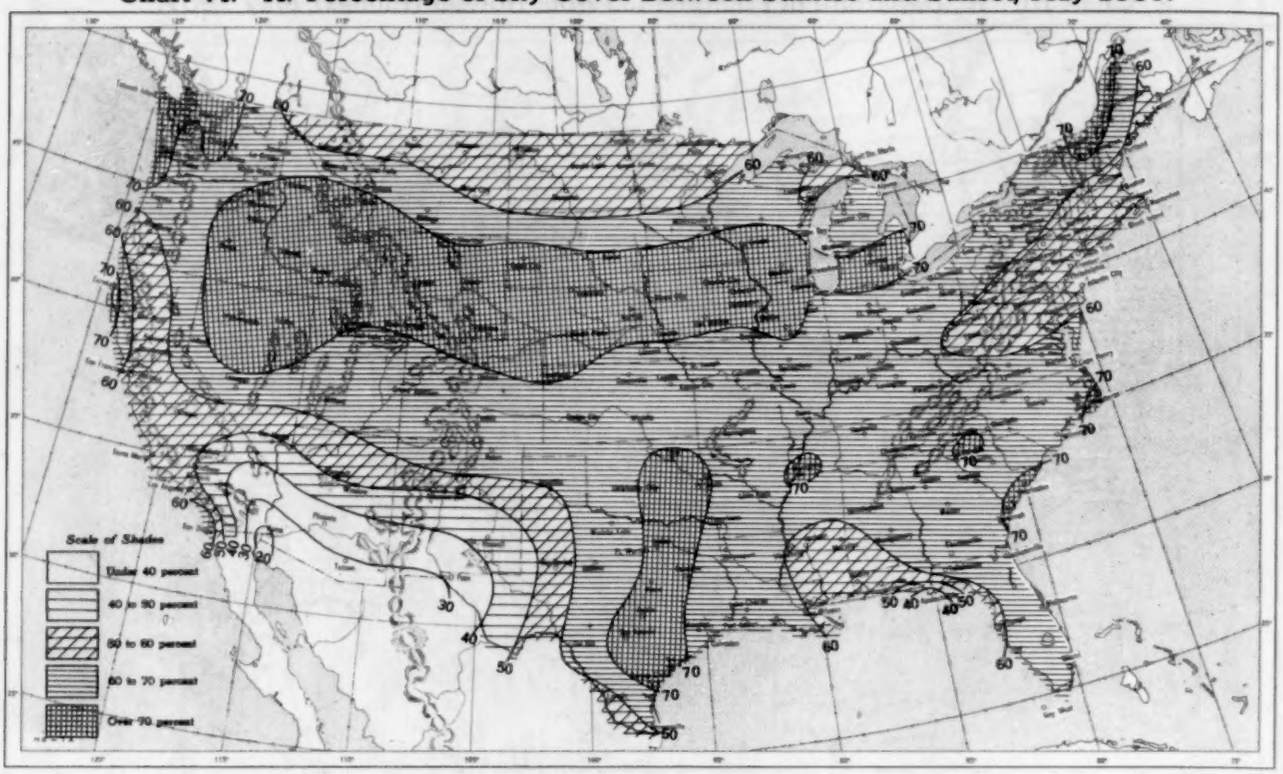


B. Percentage of Normal Precipitation, May 1957.

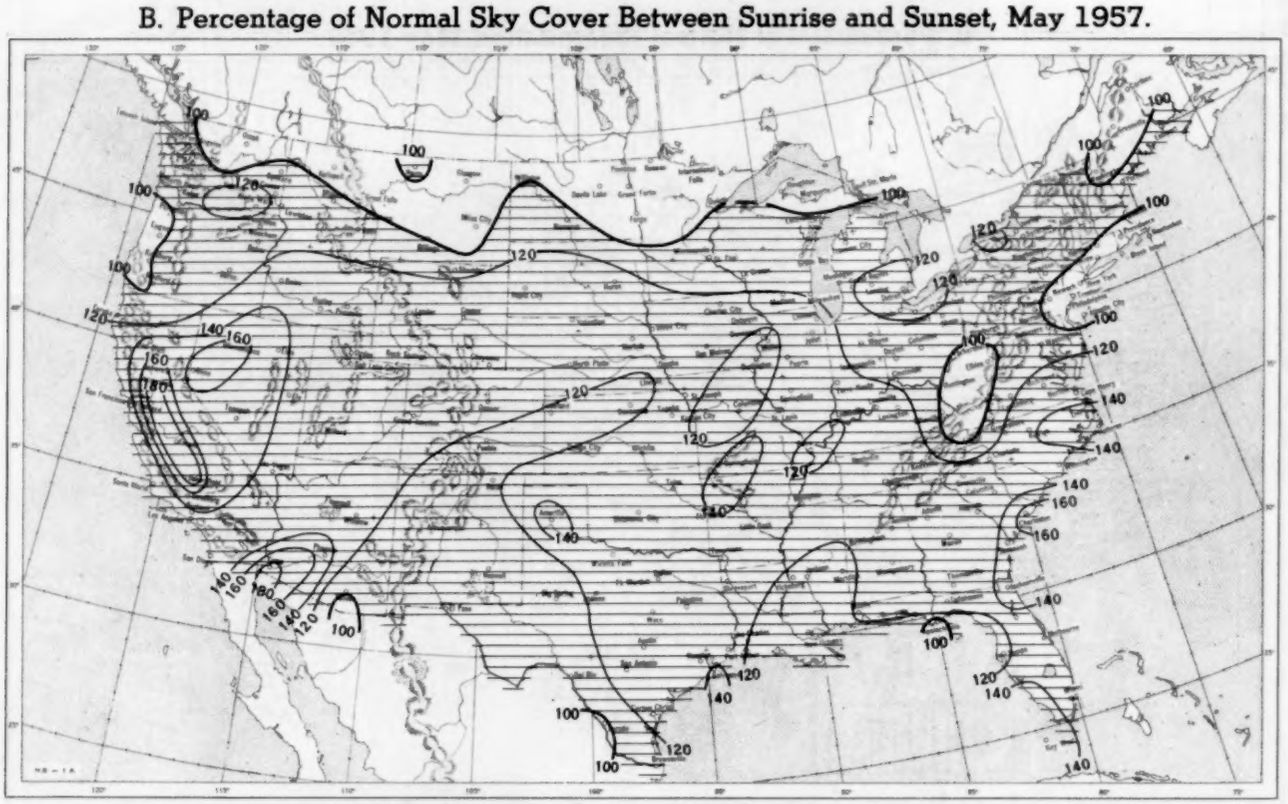


Normal monthly precipitation amounts are computed from the records for 1921-50 for Weather Bureau stations and from records of 25 years or more (mostly 1931-55) for cooperative stations.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, May 1957.

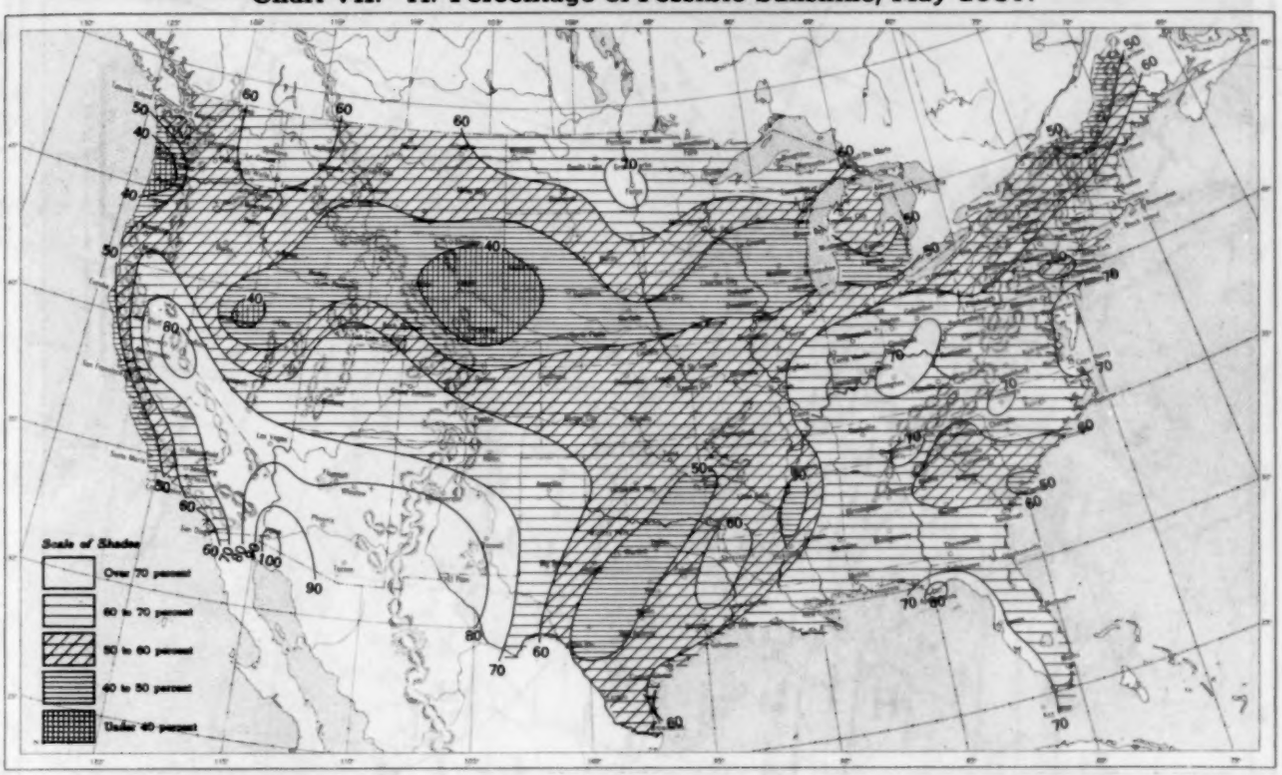


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, May 1957.

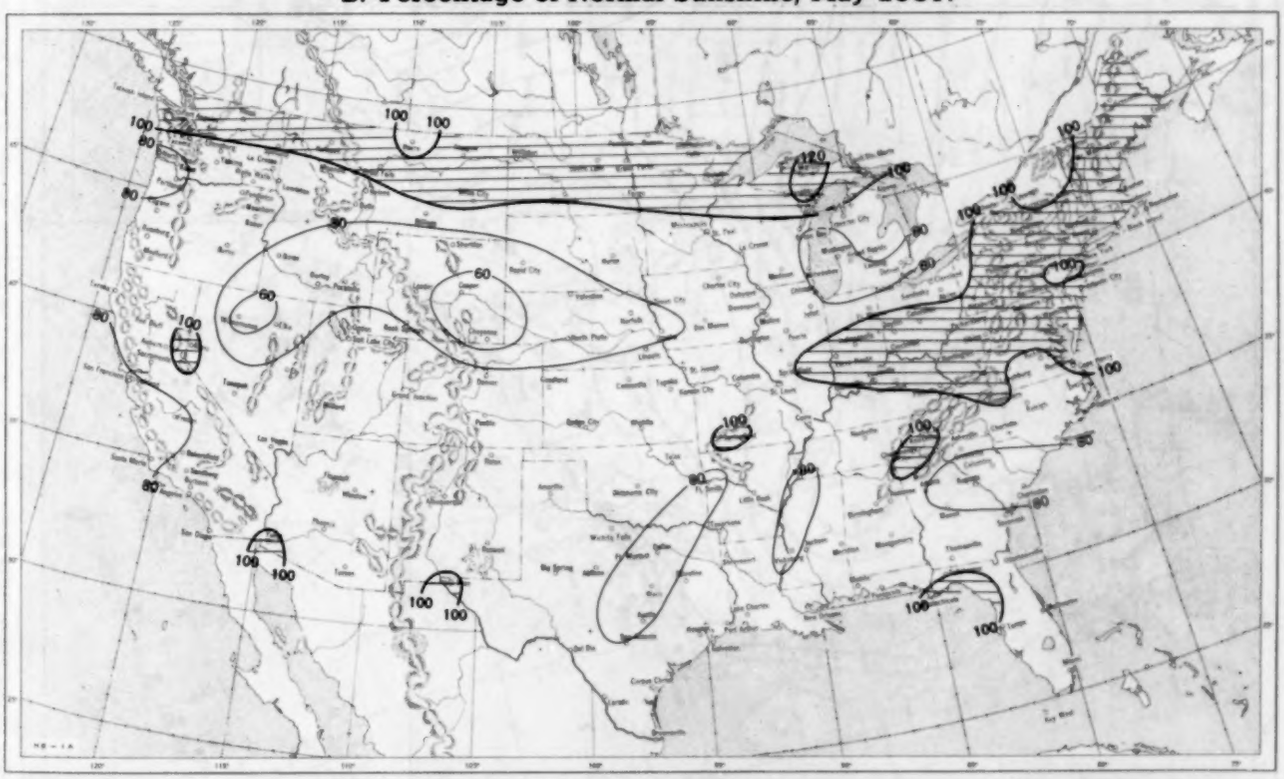


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, May 1957.



B. Percentage of Normal Sunshine, May 1957.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, May 1957. Inset: Percentage of Mean Daily Solar Radiation, May 1957. (Mean based on period 1951-55.)

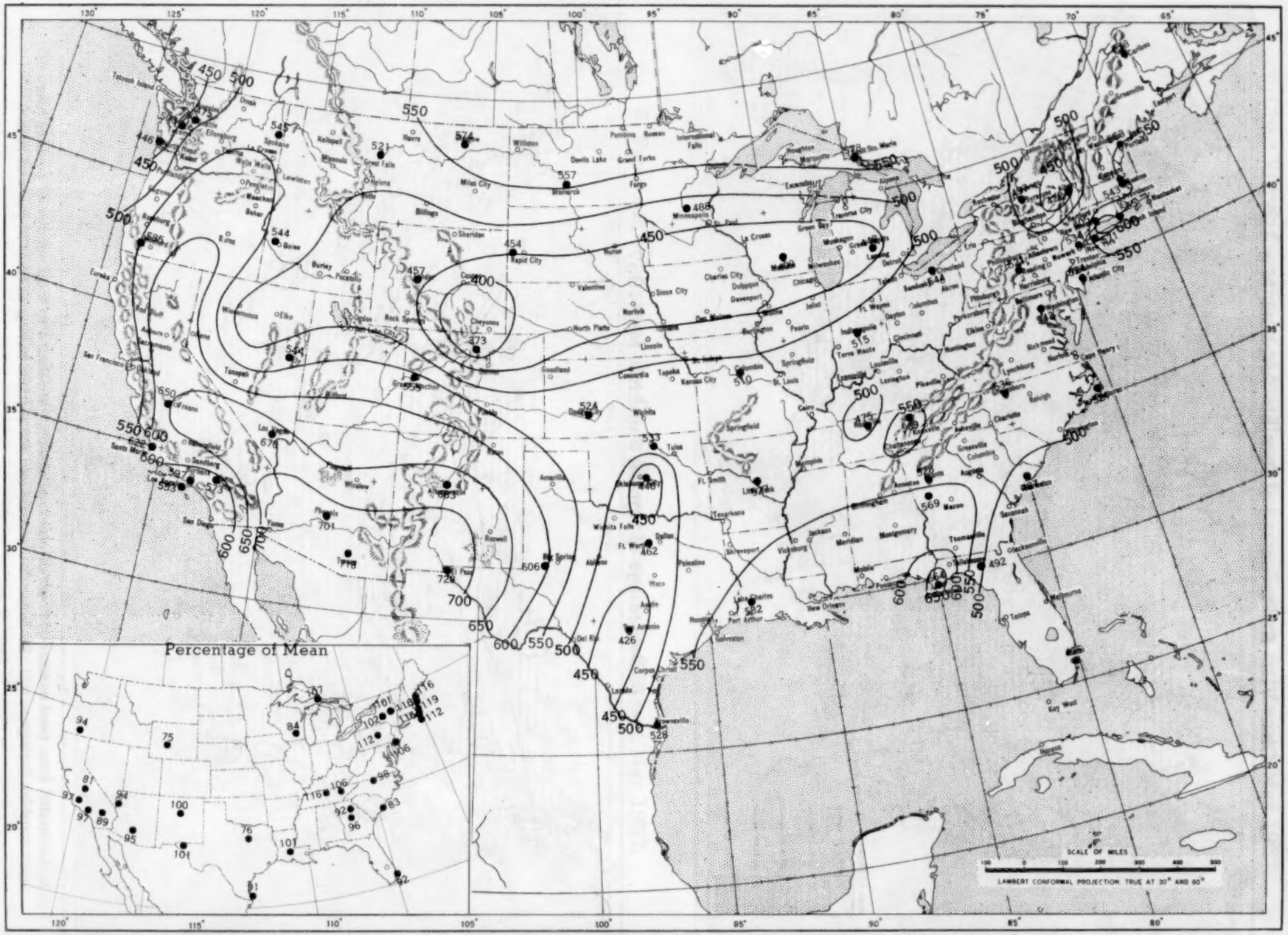
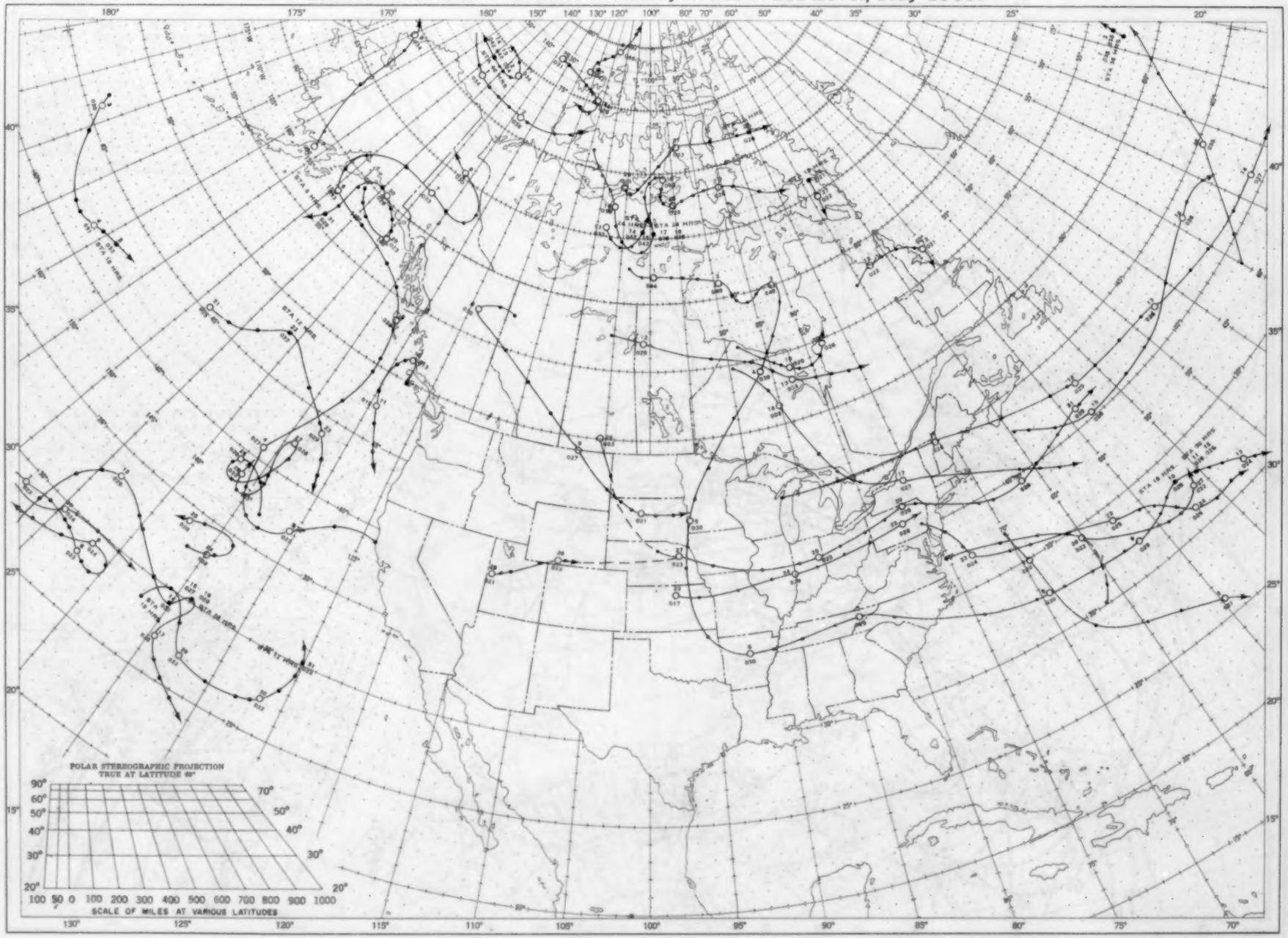


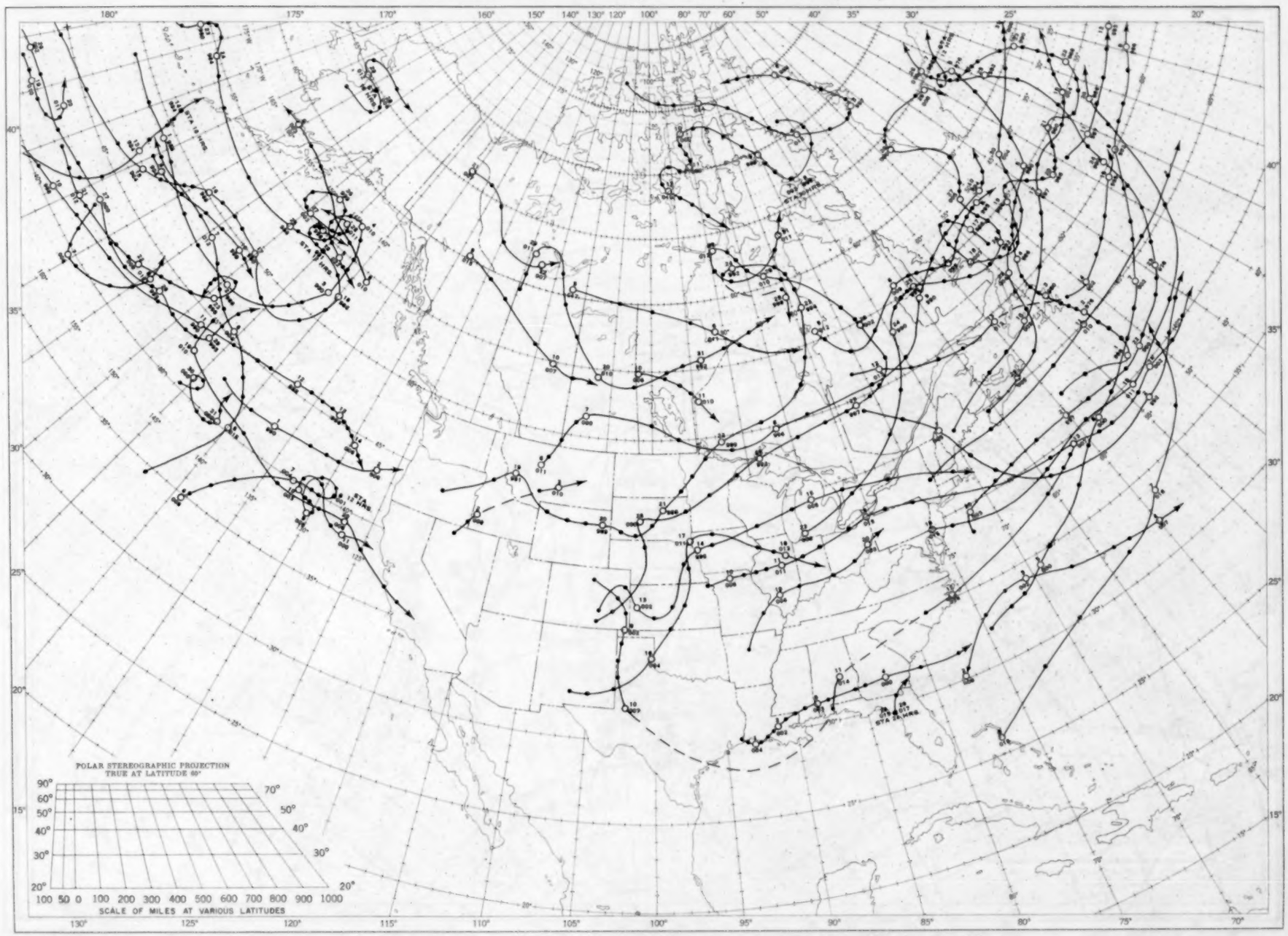
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. The inset shows the percentage of the mean based on the period 1951-55.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, May 1957.


POLAR STEREOGRAPHIC PROJECTION
TRUE AT LATITUDE 60°
90° 60° 50° 40° 30° 20°
70° 50° 40° 30° 20°
100 50 0 100 200 300 400 500 600 700 800 900 1000
SCALE OF MILES AT VARIOUS LATITUDES

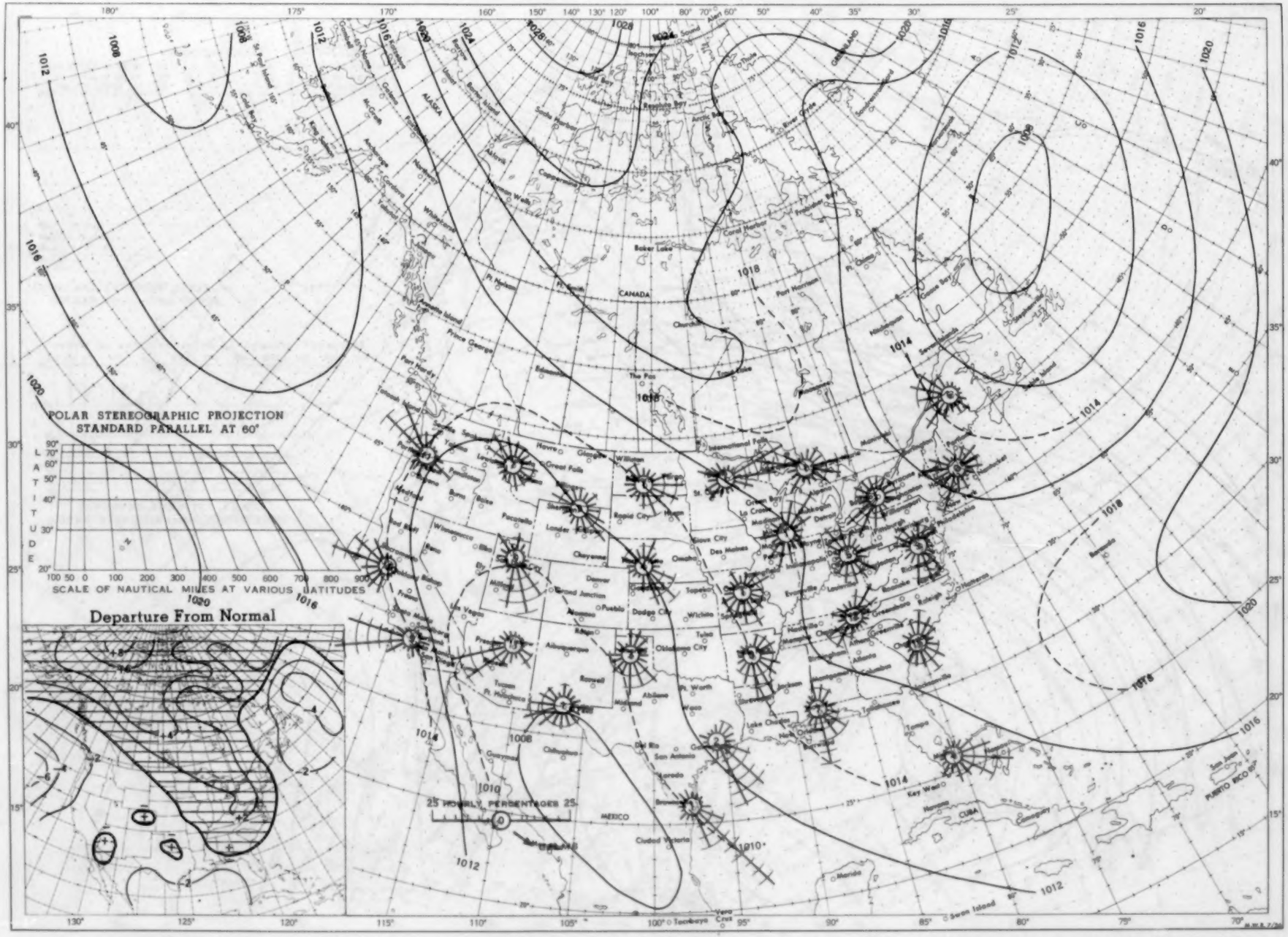
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, May 1957.


POLAR STEREOGRAPHIC PROJECTION
TRUE AT LATITUDE 60°
90° 60° 50° 40° 30° 20°
70° 50° 40° 30° 20°
100 50 0 100 200 300 400 500 600 700 800 900 1000
SCALE OF MILES AT VARIOUS LATITUDES

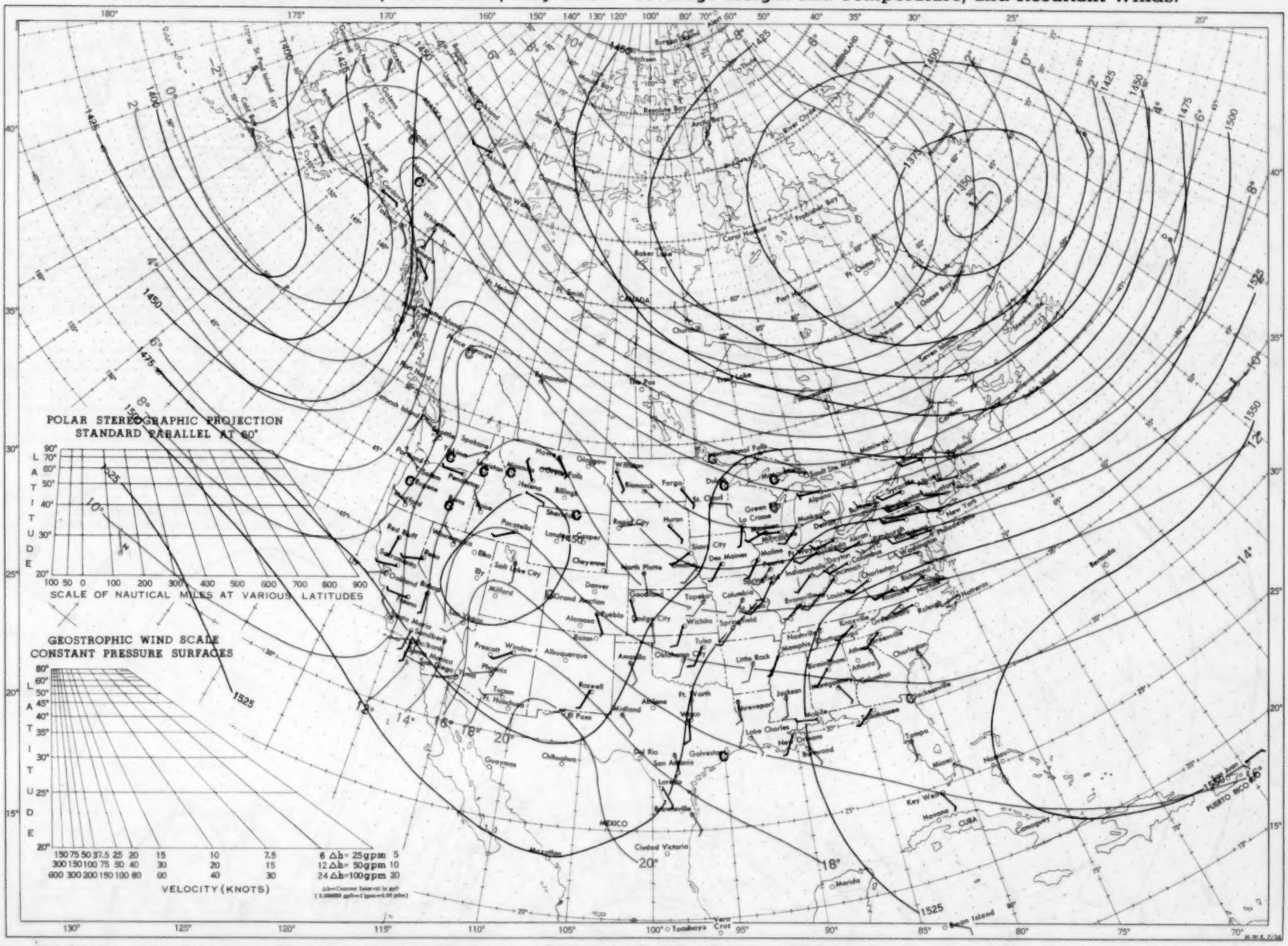
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, May 1957. Inset: Departure of Average Pressure (mb.) from Normal, May 1957.



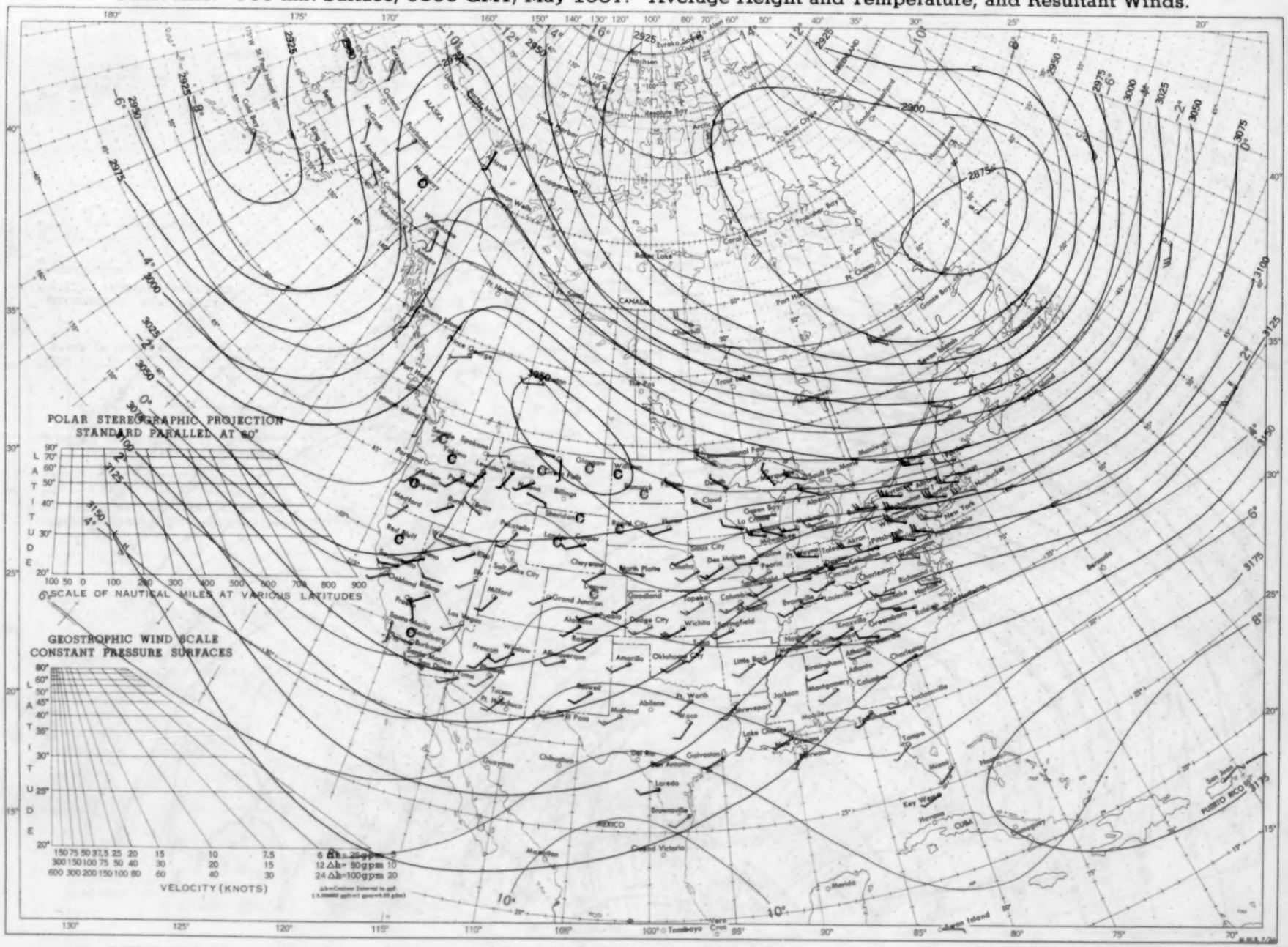
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. 850-mb. Surface, 0300 GMT, May 1957. Average Height and Temperature, and Resultant Winds.



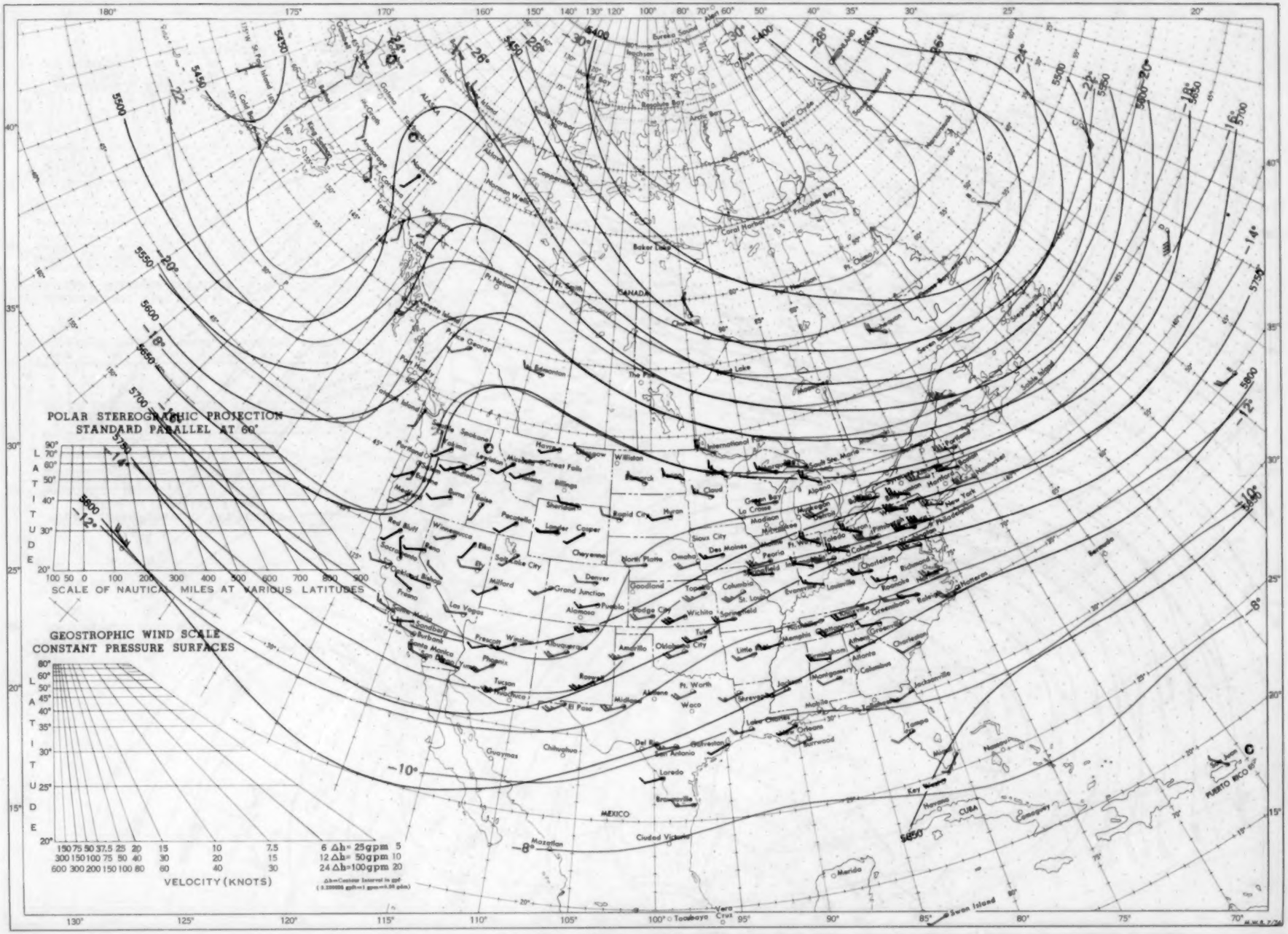
Height in geopotential meters (1 g.p.m. = 0.98 dynamic meters). Temperature in °C. Wind speed in knots; flag represents 50 knots, full feather 10 knots, and half feather 5 knots. Winds shown in red are based on rawins taken at the indicated pressure surface and time. Those in black are based on pibals taken at 2100 GMT and are for the nearest standard height level.

Chart XIII. 700-mb. Surface, 0300 GMT, May 1957. Average Height and Temperature, and Resultant Winds.



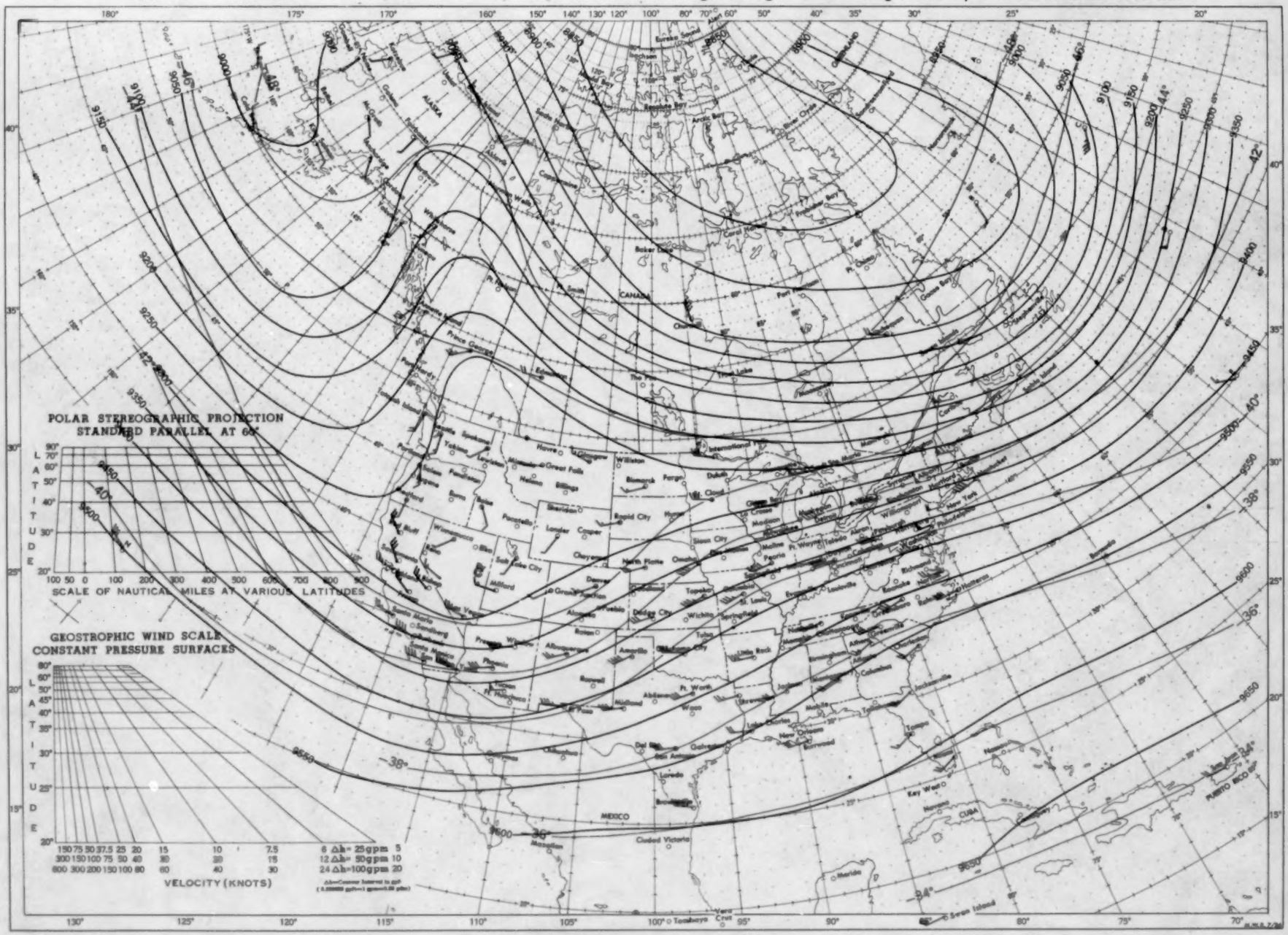
See Chart XII for explanation of map.

Chart XIV. 500-mb. Surface, 0300 GMT, May 1957. Average Height and Temperature, and Resultant Winds.



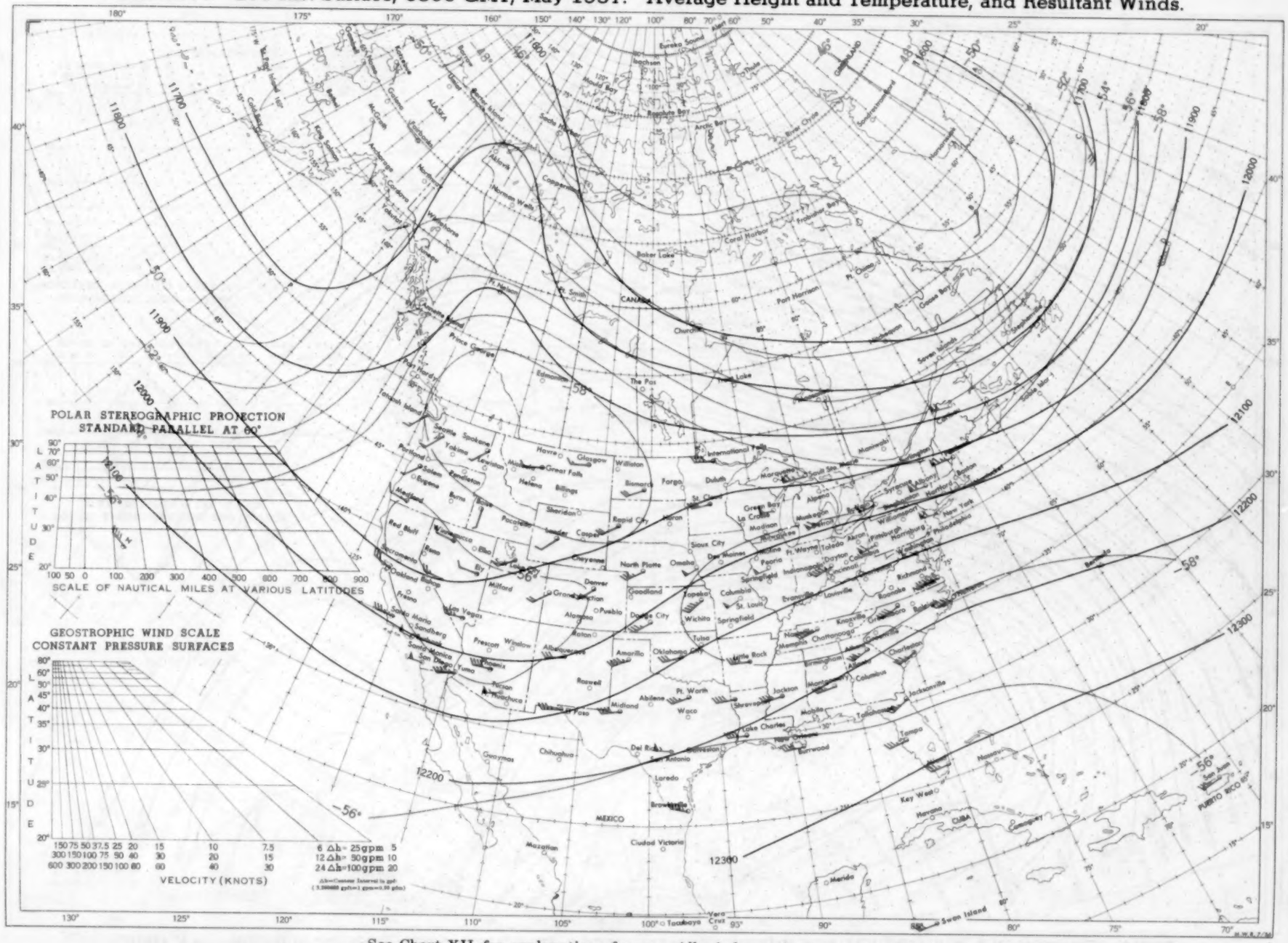
See Chart XII for explanation of map.

Chart XV. 300-mb. Surface, 0300 GMT, May 1957. Average Height and Temperature, and Resultant Winds.



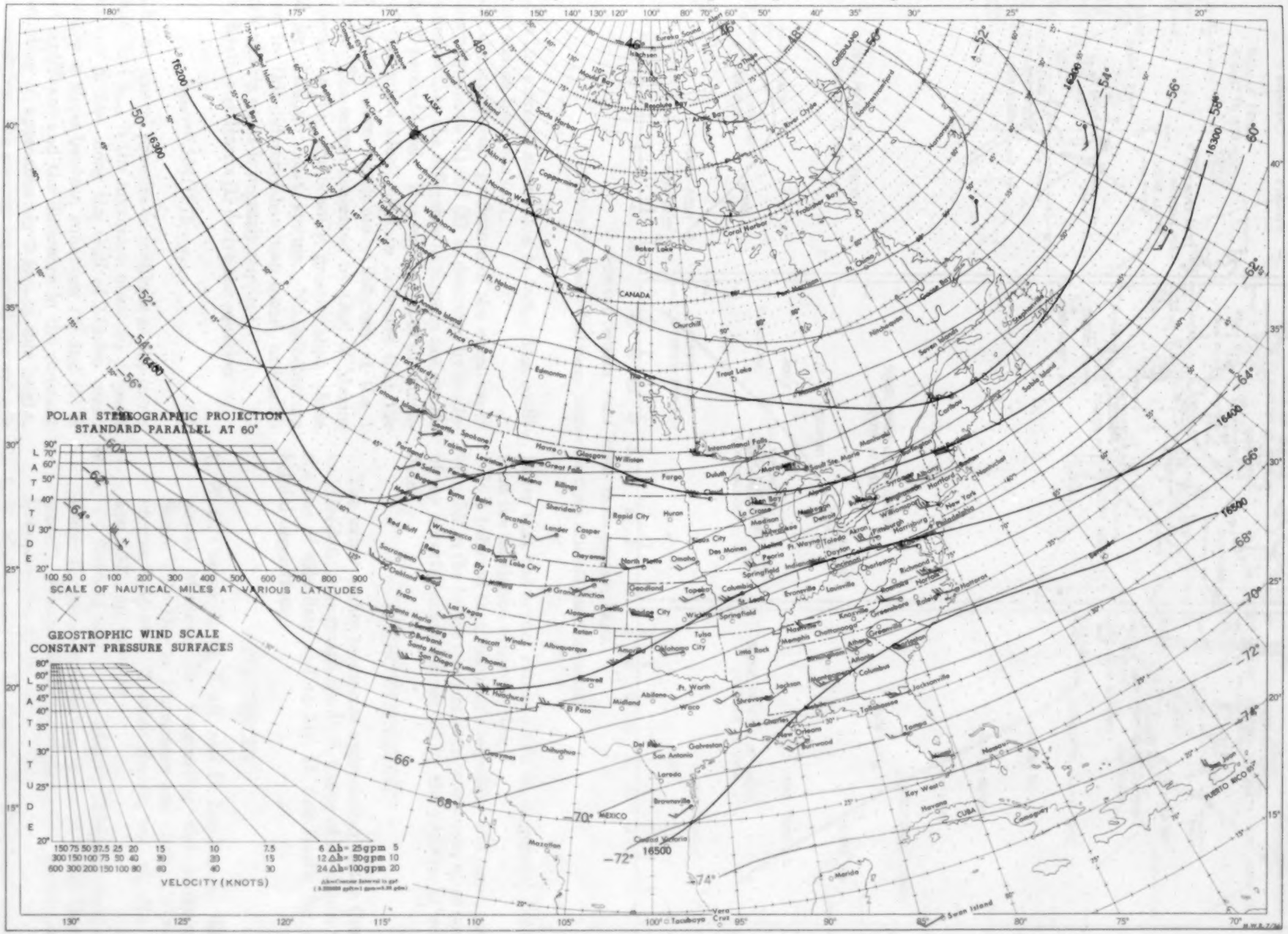
See Chart XII for explanation of map.

Chart XVI. 200-mb. Surface, 0300 GMT, May 1957. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map. All winds are from rawin reports.

Chart XVII. 100-mb. Surface, 0300 GMT, May 1957. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map. All winds are from rawin reports.

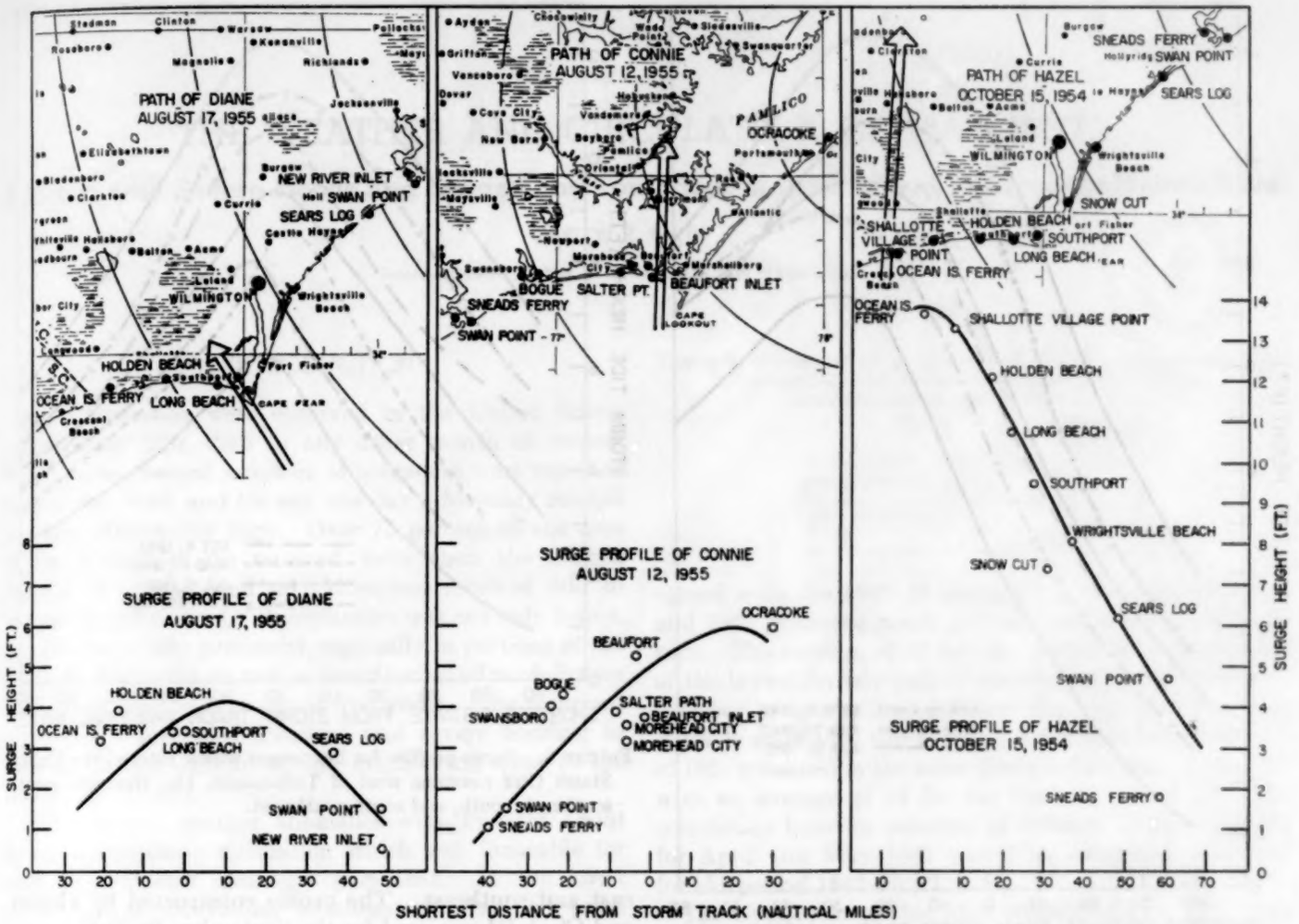


FIGURE 7.—Individual surge profiles for three Atlantic coast hurricanes.

where h_{ezt} is the extreme storm tide in feet. The coefficient of correlation here was 0.81.

A test of the statistical significance of the variation in slope between equations (1) and (2), as described by Snedecor [5], indicates that the difference in slope is not significant at the 10 percent level. However, a test of the homogeneity of the entire block of data indicates that the complete equations are significantly different at the 1 percent level. The surges generated by Gulf of Mexico storms appear to be significantly greater than those generated by Atlantic coast storms. No satisfactory explanation for this difference has been found, and additional work on this point is urgently required.

Conner, Kraft, and Harris [1] derive the equation

$$h_{max}=0.154(1019-p_o) \qquad (3)$$

where p_o is the central pressure in millibars as the storm came inland, and h_{max} is the maximum observed value of the storm tide in feet along the Gulf of Mexico coast. The difference in slope between equations (2) and (3) is clearly not significant and the difference in the constant term, amounting to approximately 2 feet in tide height, appears to result from the assumption made in the writer's paper that the actual extreme tide is, in general, higher than the maximum observed tide.

It is believed that the profile technique will prove more valuable in the future study of hurricane surges when some of the uncertainties are removed by the addition of more data.

ACKNOWLEDGMENTS

The writer wishes to express appreciation to the Coast and Geodetic Survey and the U. S. Corps of Engineers for the use of tide data and to Mr. D. Lee Harris for his helpful suggestions.

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1. W. C. Conner, R. H. Kraft, and D. Lee Harris, "Empirical Methods for Forecasting the Maximum Storm Tide Due to Hurricanes and Other Tropical Storms," *Monthly Weather Review*, vol. 85, No. 4, Apr. 1957, pp. 113–116.
2. A. C. Redfield and A. R. Miller, "Memorandum on Water Levels Accompanying Atlantic Coast Hurricanes," Woods Hole Oceanographic Institution, Reference No. 55–28, June 1955.
3. L. F. Hubert and G. B. Clark, *The Hurricane Surge*,

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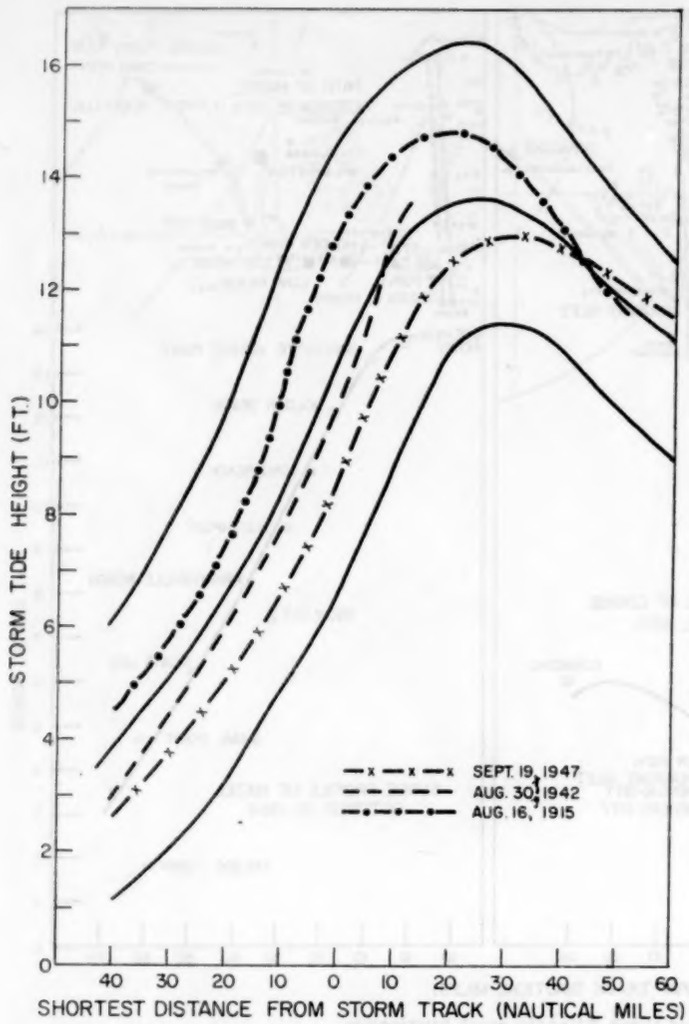

FIGURE 8.—Surge profiles for hurricanes which entered the United States Gulf coastline west of Tallahassee, Fla. from the east-southeast and southeast.

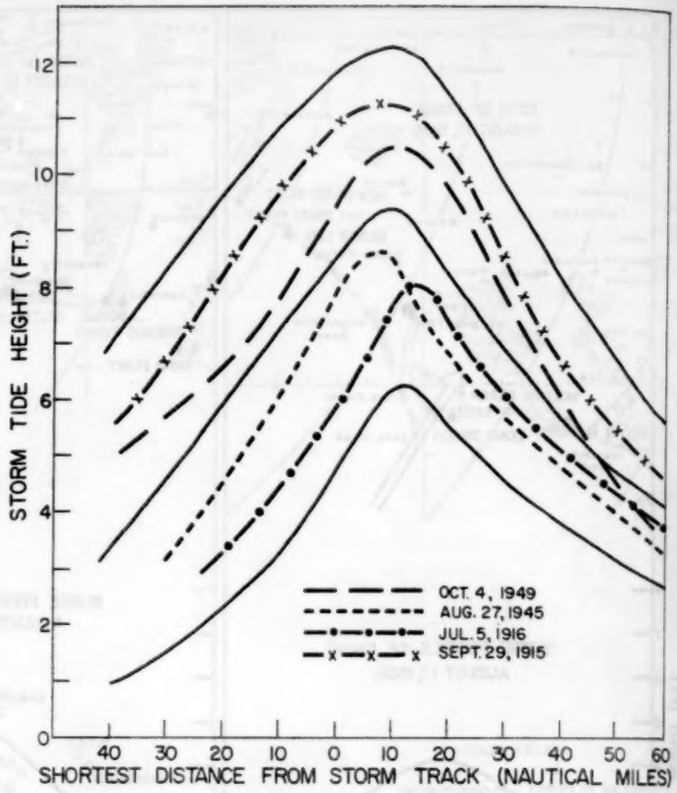

FIGURE 9.—Surge profiles for hurricanes which entered the United States Gulf coastline west of Tallahassee, Fla. from the south-southeast, south, and south-southwest.

an Interim Report, U. S. Weather Bureau, Washington, D. C., June 1955.

4. V. A. Myers, "Characteristics of United States Hurricanes Pertinent to Levee Design for Lake Okeechobee, Florida," U. S. Weather Bureau, *Hydrometeorological Report* No. 32, Washington, D. C., March 1954.
5. G. W. Snedecor, *Statistical Methods*, Iowa State College Press, 3d Ed., 1940, Chap. 12.

APPENDIX

Figures 6 and 7 contain the individual profiles for the balance of the Atlantic coast hurricanes.

Figure 8 contains the profiles for hurricanes entering the Gulf coast west of Tallahassee, Fla., from the east-southeast and southeast. The profile constructed by Hubert and Clark [3] was used for the September 19, 1947 storm. However, some of the tide values from Biloxi, Miss. westward appear to be affected by funnelling and as a result an adjustment was made to the original Hubert and Clark profile. The profile for the August 30, 1942 hurricane was made from tide data supplied by Mr. J. G. Taylor of Galveston, Tex. The following measurements were used: 3.4 ft. at 40 n. mi. to the left of the track, 4.0 ft. at 30 n. mi. to the left, 10 ft. near the center, and 13.8 ft. at 15 n. mi. to the right of the track. The profile drawn by Hubert and Clark for the hurricane of August 16, 1915 was modified somewhat by the addition of tide data supplied by Mr. Taylor.

Figure 9 contains the profiles of hurricanes entering the Gulf coast west of Tallahassee, Fla., from the south-southeast, south, and south-southwest. The profiles of Hubert and Clark were used without alteration for the hurricanes of October 4, 1949 and September 29, 1915. The surge peaks shown by Hubert and Clark for the hurricanes of August 27, 1945 and July 5, 1916 were adjusted slightly to the left to make the curves fit the data a little more closely and to make them more symmetrical.

THE WEATHER AND CIRCULATION OF MAY 1957[1]

A Month with Severe Floods and Devastating Tornadoes in the Southern Plains of the United States

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1. INTRODUCTION

More tornadoes were observed in the United States during May 1957 than in any other month of record. Furthermore, record numbers of tornadoes were reported for any one week and for any one day. Monthly rainfall was also abnormally high. Over 75 percent of the area of the United States received more than the normal amount of rainfall, and several regions received 300 to 500 percent of normal. Precipitation was not only heavy, but also unusually persistent, especially in portions of the Southern Plains where two or more inches of rainfall were reported in each of four out of five weeks. The recurrent heavy rains produced frequent and severe flooding in parts of Texas, Oklahoma, and neighboring areas to the east and northeast.

These severe weather anomalies were brought about by an atmospheric circulation which was favorable for such activity and unusually persistent. In the lower troposphere a prevailing southeasterly flow advected moist tropical air over most of southeastern and central United States. In the mid-troposphere cyclonic conditions prevailed over the western United States and anticyclonic circulation over the East. In the upper troposphere a strong jet stream flowed from an area of maximum winds over northwestern Mexico across the southern Plains to New England. Under this circulation pattern, cold maritime Pacific airmasses frequently occupied the West, while maritime tropical airmasses dominated the Southeast.

2. 30-DAY MEAN CIRCULATION

Namias [7, 8] found that for the United States area during the period 1942 to 1954 there was a minimum of persistence of certain climatic anomalies from April to May. For the longer period, 1893 to 1953, Enger [3] found no minimum of persistence from April to May. Most recently there has been a return toward the greater persistence which must have characterized the earlier years prior to 1942. This is indicated in table 1 which gives the number of stations out of 100 selected cities which remained in the same or adjacent temperature classes from April to May. Although the year 1956 [6] agreed with the 1942–54 average [7], the years 1955 [16] and 1957 produced much greater persistence in temperature. The average of 57 for the period 1942–54 was one of the lowest for any pair of months during the year.

TABLE 1.—*Measure of persistence of monthly mean temperature anomalies in the United States from April to May*

Period	Persistence (percent)
Average 1942–1954	57
1955	98
1956	52
1957	83

Other measures also indicate the high persistence of climatic anomalies this spring. Forty-eight stations (out of 100) remained in the same precipitation class, compared with an average of 33 for the 1942–50 period [7]. The correlation between patterns of 700-mb. height anomaly for April and May 1957 was 0.50, compared with 0.20 for the period 1942–50 [7].

The circulation of this May considered over the entire Northern Hemisphere exhibited several noteworthy features. The largest anomaly was a positive 360-ft. center associated with a pronounced blocking anticyclone in Russia (fig. 1). Positive anomalies of the blocking variety were also observed over the entire Arctic with extensions southward through Alaska and Greenland. Rex [9] found blocking to be common in May, and many previous authors in this series of articles have emphasized the predominance of blocking at this season [4, 5, 15, 16].

This May high-latitude blocking and accompanying easterlies in polar latitudes (55° N.–70° N.) (fig. 2) were strongest at mid-month. Early and late in May polar westerlies existed—a more normal situation. The subtropical westerlies (20° N.–35° N.) persisted above normal as a result of the expanded circumpolar westerlies associated with higher than normal 700-mb. heights in the Arctic. The subtropical and temperate index curves were in phase with each other but 180° out of phase with the polar westerlies. Temperate westerlies were subnormal early in May, then increased and remained above normal at an almost constant value during most of the month, before returning to subnormal values at the end of May. This lack of week-to-week variability was indicative of the persistent circulation that existed during most of May.

[1] See Charts I-XVII following p. 192 for analyzed climatological data for the month.

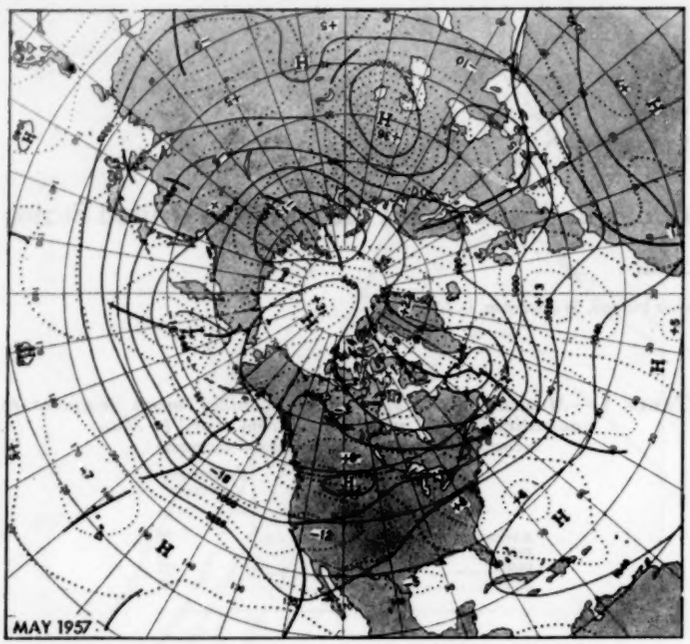

FIGURE 1.—Mean 700-mb. contours and height departures from monthly normal (both in tens of feet) for May 1957. Cyclonic conditions and subnormal heights in western United States and anticyclonic conditions and above normal heights in the East combined to produce widespread heavy precipitation and severe weather.

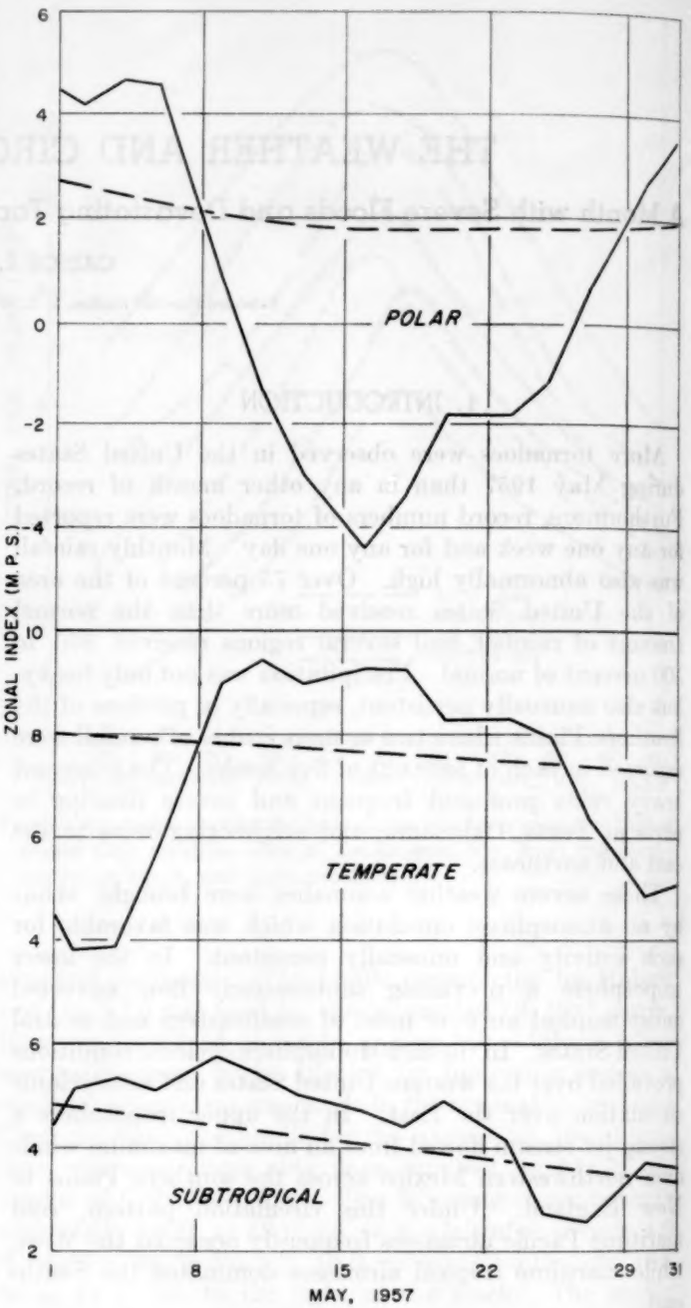

FIGURE 2.—Time variation of 700-mb. westerlies (in meters per second) over the Western Hemisphere for polar (55° N.–70° N.), temperate (35° N.–55° N.) and subtropical (20° N.–35° N.) belts. Solid lines connect 5-day mean index values (plotted at middle of 5-day period and computed three times weekly), and dashed lines show variation of corresponding normal indices. At mid-month easterlies prevailed in the polar region while above normal westerlies dominated other regions—a manifestation of the expanded circumpolar vortex.

The mean circulation over North America (fig. 1) had a confluent configuration which was similar to, but more pronounced than, that found on the normal chart [12]. In Canada a ridge was observed in the west and a trough in the east. The opposite was true in the United States, where there was a trough with subnormal heights along the west coast and a ridge with above normal heights in the East. The trough-to-trough wavelength across the United States was abnormally long (66° of longitude at 35° N. and 102° of longitude at 45° N.). The broad, eastward extent of cyclonic circulation gave rise to frequent periods of storminess in the Southern Plains. The below normal heights which extended eastward from the west coast to the Mississippi Valley were particularly significant in showing the eastward penetration of low-latitude disturbances, even though a mean trough was not observed over the continent.

The major features of the 700-mb. geostrophic wind field (fig. 3A), like those of the 700-mb. height pattern, were located near their normal positions, but the magnitude of the winds was quite anomalous (fig. 3B). For example, the two axes of maximum wind speed over North America averaged very close to the normal locations, although wind speeds along these axes were greater than normal (fig. 3B). One air stream flowed southeastward out of northwestern Canada and the other northeastward from northern Mexico to combine into a single jet stream near Nova Scotia. Wind speeds were above normal along the jet stream axes over the United States, especially in the Southwest. The major negative anomalies were subnormal wind speeds in the Northern Plains and Rocky Mountain States. The quasi-stationary position of the jet stream, in addition to its greater than normal strength, had a pronounced effect on the monthly weather (to be discussed later).

The jet stream was better delineated and wind speeds along its axis were stronger in the upper troposphere than at the lower levels. At 200 mb. the jet stream axis was

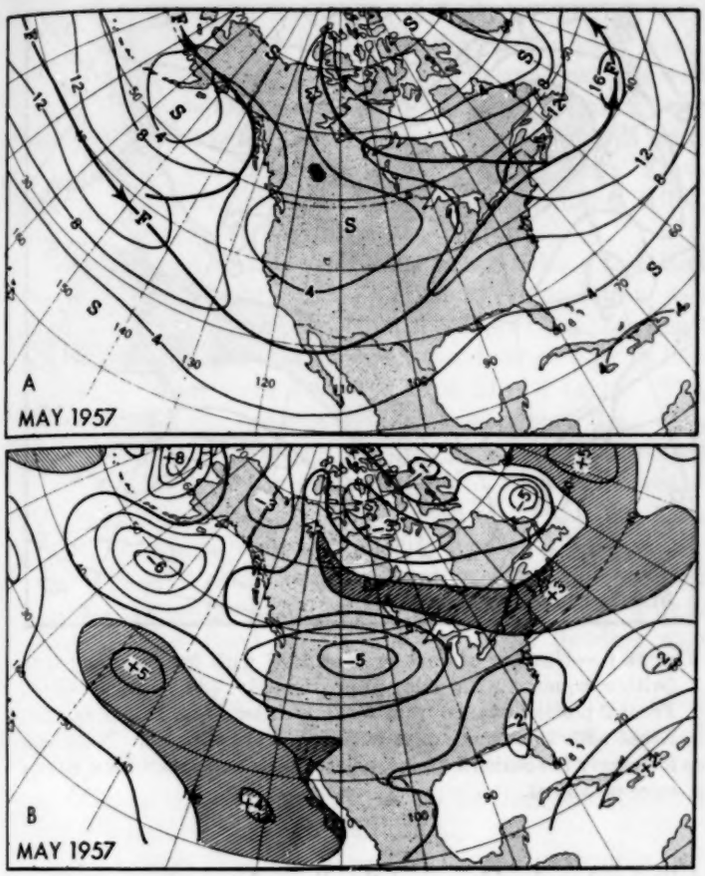

FIGURE 3.—(A) Mean 700-mb. isotachs and (B) departure from monthly normal wind speed (both in meters per second) for May 1957. Solid arrows in (A) indicate principal axes of maximum winds at 700 mb. Anomalies in (B) greater than +2 are hatched. A confluent pattern, similar to the normal, existed over North America, but wind speeds averaged greater than normal along the jet stream from northern Mexico to Maine.

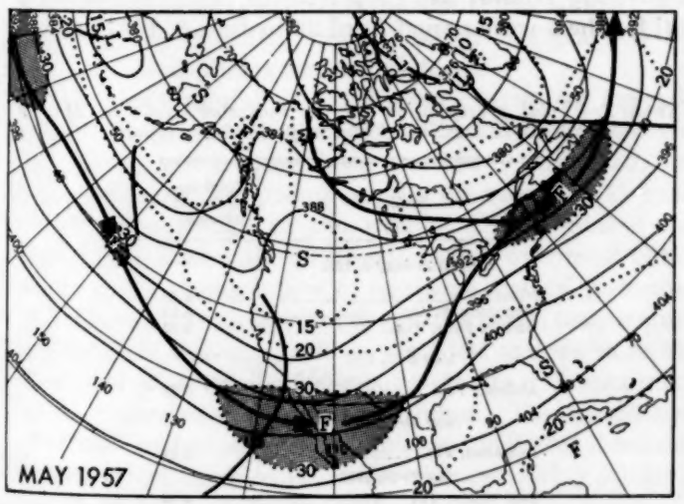

FIGURE 4.—Mean 200-mb. contours (solid, in hundreds of feet) and isotachs (dotted, in meters per second) for May 1957. Wind speeds greater than 30 m. p. s. are stippled. Solid arrows indicate the average position of the 200-mb. jet stream. Wind speed maximum observed over northern Mexico, so that regions of the Southwest were downstream from an area of maximum winds.

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located rather far south in the West, and the strongest winds were centered over Mexico (fig. 4). If this mean isotach pattern indicates the preferred daily wind field (and an examination of the daily weather maps revealed that it does), then southwestern United States was frequently located under the left front quadrant of the jet maximum (north of the jet axis and downstream from the maximum wind). This is the most likely area of high-level divergence and stormy weather according to Riehl [10] and Beebe and Bates [2].

The contour pattern at 200 mb., which resembled the one at 700 mb., had a deep trough with cyclonic vorticity in the Far Southwest and a flat ridge in the East. The confluent pattern was also discernible at this level, with broadscale northwesterly flow observed over Canada and southwesterly flow over the United States.

The monthly mean sea level chart (Chart XI) had some rather interesting and important features. Pressures averaged below normal over most of the United States and above normal over Canada and the Arctic. This configuration of anomalies was a reflection of the high-latitude blocking and expanded circumpolar vortex referred to previously. Another surface feature, especially noteworthy from the standpoint of precipitation, was the broadscale southeasterly flow over a large area of the United States. It was particularly strong in the central Plains where it had an upslope component.

In addition to the flow patterns, the associated thermal field was conducive to cyclonic activity. Cold maritime Pacific airmasses dominated the Southwest and kept the thickness (700–1000 mb.) below normal (fig. 5), but in the East maritime tropical airmasses dominated, and the thickness averaged above normal. The southern boundaries of the subnormal thickness corresponded approximately with the upper jet stream axes (fig. 4) and also with the band of high frequency of surface fronts (fig. 6). The cold-in-the-West, warm-in-the-East temperature pattern, with the frontal zone frequently in the Southern Plains, combined with the overlying jet stream and planetary wave to form an ideal set-up for heavy precipitation and severe weather in the central United States.

3. WEATHER OF THE MONTH AND ITS RELATION TO THE MEAN CIRCULATION

Precipitation was heavy and widespread during May and most areas reported more than normal amounts (Charts II, III). Several stations, including Prescott, Ariz., Blue Canyon and Santa Maria, Calif., Pueblo, Colo., Macon, Ga., Fort Worth and San Antonio, Tex., and Pocatello, Idaho reported the wettest May on record. Less significant rainfall statistics, such as, second wettest May, most precipitation in recent years, and record amounts for 24-hour periods, were noted by many stations. The largest amounts of precipitation for May (Chart II) were located along the band of high frequency of surface fronts (fig. 6) in Arkansas, Missouri, Oklahoma, and central Texas. Over 12 inches of precipitation were

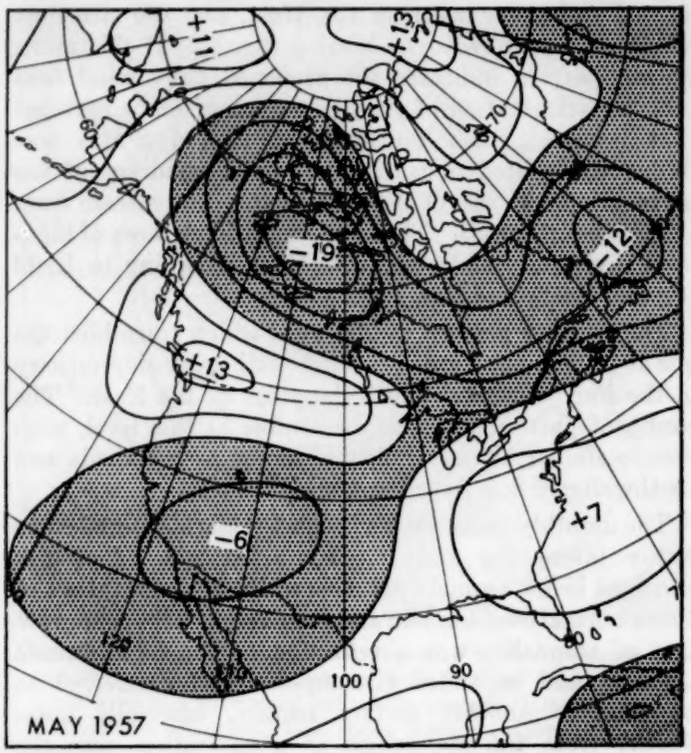

FIGURE 5.—Departure from normal of mean thickness (1000–700 mb.) for May 1957, with subnormal values stippled. Isoline interval is 50 feet and centers are labeled in tens of feet. Cold air dominated the Southwest and warm air the East, with their common boundary frequently located over the Great Plains.

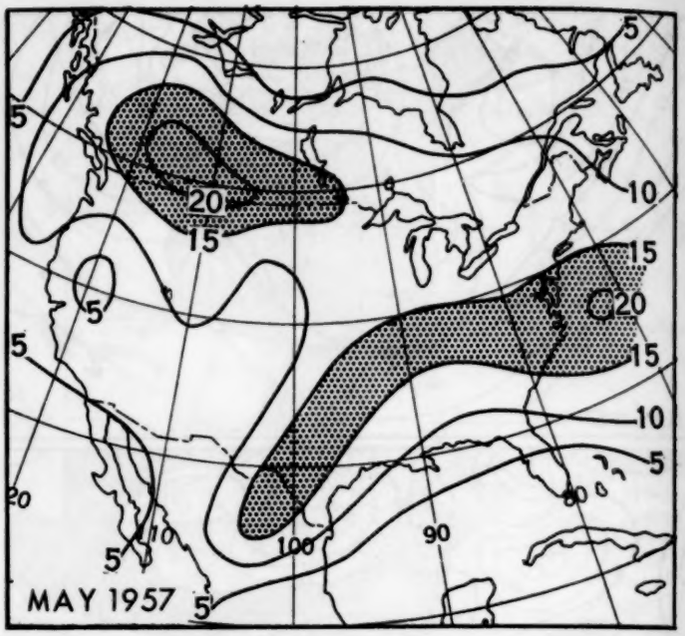

FIGURE 6.—Number of days in May 1957 with fronts of any type (within squares with sides approximately 430 nautical miles). Frontal positions taken from *Daily Weather Map*, 1:30 p. m., EST. Areas with 15 or more days with fronts are stippled. Note high frequency in southern Plains, where floods and severe local storms were prevalent.

reported by stations in Texas and Oklahoma, and as much as 10 inches in the Southeast around Georgia. This rainfall in the Southeast, which was as much as 300 percent of normal, occurred under subnormal monthly westerlies (fig. 3B), indicative of the fact that onshore flow at low levels was quite prevalent.

Over southern California stronger than normal westerly flow with cyclonic curvature (figs. 1 and 3B) enhanced orographic lifting, and 200 to 500 percent of normal rainfall was reported. Another contributing factor to the California rains was cyclonic activity at sea level at unusually low latitudes along and off the coast (Chart XI).

In general, precipitation this May was not only abnormally heavy but also very persistent in many regions of the United States. Rainfall was most persistent in a small area of Oklahoma which reported two or more inches in each of six out of seven weeks during the period April 15 to June 2, 1957 (fig. 7). A larger area composed of parts of Texas, Oklahoma, and Arkansas had two or more inches of rain in each of four weeks out of the same 7-week period. Some extremely large totals in inches for five weekly periods (mostly in May) are given in table 2.

Throughout the first half of May heavy rainfall was reported in the Southeast and southern Great Plains. During the fourth week (May 20–26) record-breaking rains continued in the southern Great Plains and extended into the middle Mississippi Valley. These excessive rainfalls produced widespread flooding of record proportions. The large, short-period (6 to 24 hours) precipitation amounts accompanying the violent convective activity resulted in numerous flash floods. The longer-period (1 to 7 weeks) almost continuously heavy amounts maintained many of the rivers in the southern Great Plains at flood or near flood stages during the entire month. A brief summary of weekly flood reports which appeared in the *Weekly Weather and Crop Bulletin, National Summary* [14] for the 5-week period April 29 to June 2, 1957 follows.

TABLE 2.—*Total precipitation for the indicated weeks in May at stations in the United States (preliminary report)*

Station	Total precipitation (inches)
April 29–May 5, 1957	
Miami, Fla.	9.52
Montgomery, Ala.	6.35
Wichita Falls, Tex.	5.07
May 6–12, 1957	
Abilene, Tex.	5.75
May 13–19, 1957	
Lakeland, Fla.	5.84
May 20–26, 1957	
Fort Worth, Tex.	8.49
Little Rock, Ark.	8.90
Shawnee, Okla.	6.56
Owensboro, Ky.	7.07
Rapid City, S. Dak.	4.35
May 27–June 2, 1957	
Madill, Okla.	6.57
San Antonio, Tex.	7.42

First week, April 29–May 5.—"Shower activity, continuing in Texas and Oklahoma during the past week, caused most streams in eastern and central Texas as well as in portions of Oklahoma and Arkansas to maintain very high flows. Flooding continued on major streams with moderate to severe lowland overflow resulting. Flash flooding also was reported on the Wichita River tributaries in vicinity of Wichita Falls, Tex.

"By the end of the period the lower Sabine and Red Rivers had still not crested and heavy inundation was reported on the Red River below Shreveport, La., at Grand Ecore and Alexandria, La., where flood crests 9 to 10 feet over flood stage were indicated from May 7 to 11. The Sabine River was nearing crest at Logansport, La., at a stage near 40 feet, 15 feet over flood stage. The forecast crests for the Red River are the second highest of record exceeded only by the record flood of 1945. At East Point, La., 250 families have been evacuated."

Second week, May 6–12.—Flood threats continued in Texas. A downpour of over 6 inches resulted in a devastating flash flood at Lampasas. Local flooding also was reported at Denver, Colo.

Third week, May 13–19.—Critical flooding developed during this week in Oklahoma. 13.07 inches of rain fell in 24 hours at Hennessey. The worst flood on record was reported on the Cimarron River. Flooding also occurred in Kansas, Montana, and California.

Fourth week, May 20–26.—This was an extremely bad week as record-breaking rainfall covered the southern Great Plains and extended into the Mississippi Valley. Floods reintensified in Texas and Oklahoma, and were now also reported in Arkansas, Kentucky, and Tennessee.

Fifth week, May 27–June 2.—Widespread flooding occurred in Arkansas and eastern portions of Texas and Oklahoma.

These heavy rains during May definitely alleviated, except for small regions in western Texas and New Mexico, the extended drought which has plagued the southern Great Plains for several years.

The heavy rainfall in the United States was logically related to the circulation, since the following observed conditions, which have been previously discussed, are well recognized as precipitation "producers": (1) mid-tropospheric trough in the western United States and ridge in the East with southwesterly flow over most of the country, (2) strong inflow of maritime tropical airmasses at low levels, (3) surface fronts and horizontal temperature gradients, in this case, cold in the West and warm in the East, and (4) overlying 200-mb. jet stream with maximum winds upstream from the storm area. The interaction of these meteorological parameters will be discussed further when the circulation for the week May 20–26 is examined in the following section.

Concomitant with the heavy rainfall in the southern and central Plains was record-breaking severe storm activity. During May 1957 approximately 231 tornadoes were reported, an all-time record (records start in 1916 [13]). The previous high for May is 219 tornadoes which

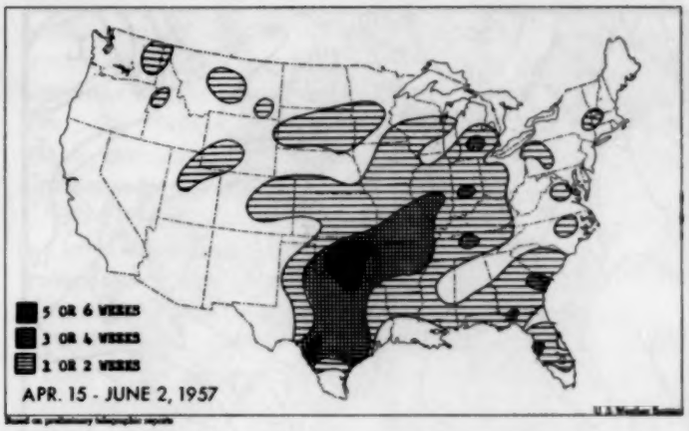

FIGURE 7.—Number of weeks during the 7-week period April 15–June 2, 1957 that the total weekly precipitation was two or more inches. Rainfall was abnormally persistent in the southern Plains, for some areas received two or more inches in as many as five or six weeks during this period.

was observed in 1955 when the circulation was quite similar to that of this May [16]. This month's circulation pattern with a ridge in the East and trough in the West is very similar to the circulation that existed during other Mays when tornadoes were common, namely in 1955, 1953, 1949, and 1933. After comparing monthly mean 700-mb. circulations with the tornado records from 1933 to 1957, the author is convinced that an extremely good relation exists between these large-scale averaged flow patterns and local severe storm activity measured over a similar time period.

There was considerable week-to-week variability in the number of tornadoes reported (table 3). The most severe weather occurred during the fourth period (May 20–26) when 124 tornadoes were observed. The majority of tornadoes this May occurred east of the Rocky Mountains and west of the Mississippi River, although there were a few widely scattered tornadoes over many other parts of the United States. The region of most dense incidence was Oklahoma, northern Texas, and Kansas. Neighboring States reported smaller but sizeable numbers of tornadoes.

Although tornadic activity and flooding in the Plains dominated the weather picture for seven consecutive weeks starting April 15, there were noteworthy reports early in May of minor droughts and forest fires in New England and the Middle Atlantic States. The first week of May the forest fire hazard intensified in New England and most forests were "closed." The period from April 9

TABLE 3.—*Number of tornadoes for the indicated weeks in May 1957 (preliminary reports)*

Week in 1957	Number of tornadoes
April 29–May 5	40
May 6–12	25
May 13–19	49
May 20–26	124
May 27–June 2	49

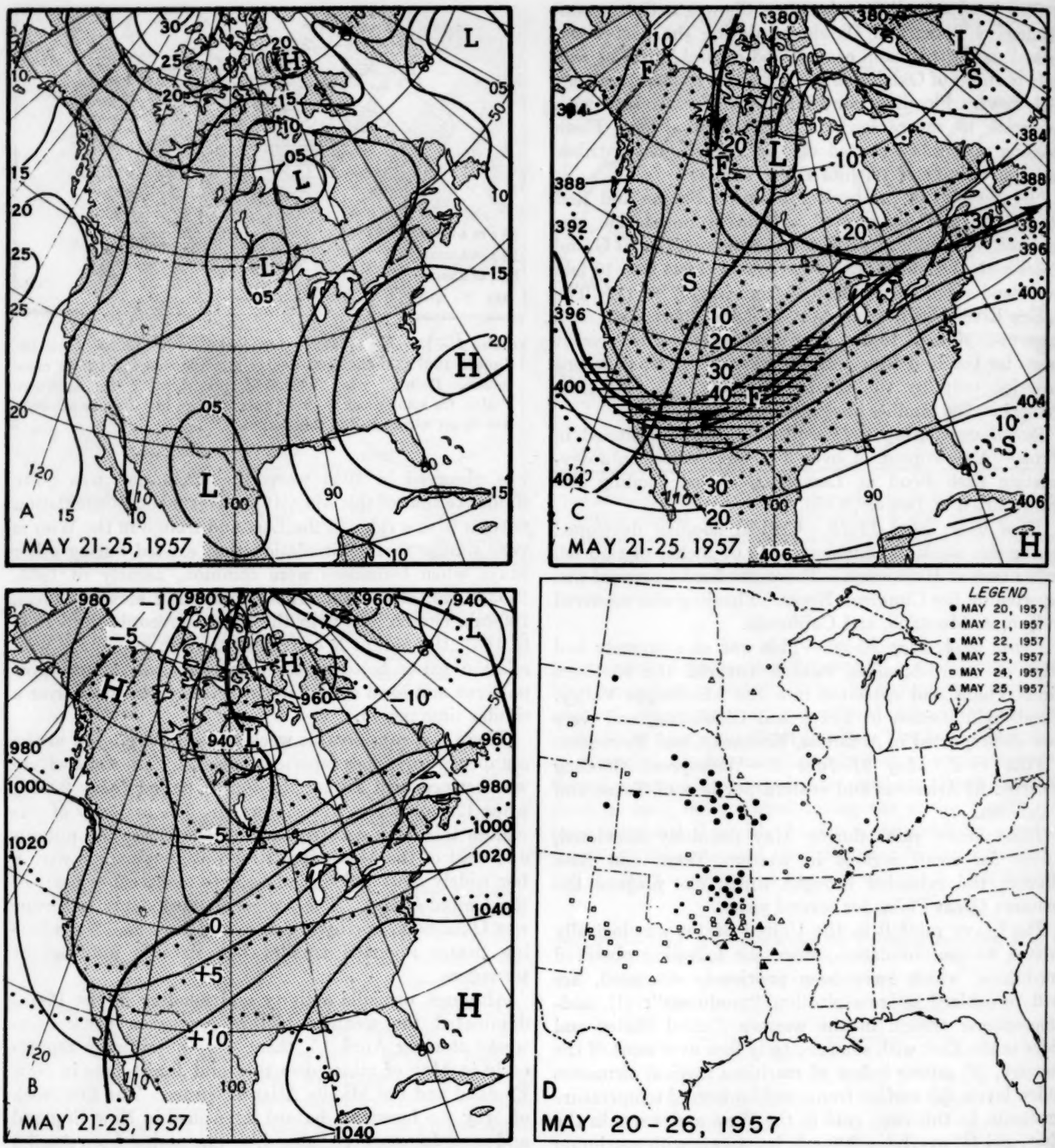

FIGURE 8.—(A) Five-day mean sea level isobars (in millibars with hundreds omitted). Sharp trough over Great Plains was flanked by pronounced ridges along both coasts of United States. (B) Mean 700-mb. contours (solid, in tens of feet) and isotherms (dotted, in ° C.). Configuration of both the contours and isotherms was favorable for heavy rain and severe weather in the southern Plains and central Mississippi Valley. (C) Mean 200-mb. contours (solid, in hundreds of feet) and isotachs (dotted, in meters per second). Wind speeds greater than 40 m. p. s. are hatched. Pronounced jet maximum over the Southwest was conducive to severe weather in the Plains. A, B, and C all for the period May 21-25, 1957. (D) Location of tornadoes reported over the United States during the week May 20-26, 1957, a record for any week. Symbols indicate the date of occurrence. Note the large numbers on May 20 and 24. None were reported on May 26. Data furnished by Office of Climatology, U. S. Weather Bureau. These are early reports and subject to minor change.

to May 10 was the driest 30-day period in April and May on record at the Blue Hill Meteorological Observatory (Milton, Mass.) [17]. During the second week, rains in New England relieved dry conditions and removed the forest fire problem, but little or no precipitation occurred in the Middle Atlantic States and fire hazard conditions mounted. However, during the third week widespread rains over most of the northeastern United States alleviated the drought in both regions.

In contrast to the interesting precipitation regime of May, the temperature picture contained few highlights. Average temperature anomalies for the month (Chart I-B) were small, and the weekly departures were not extreme, one of the largest being only −12° F. in Utah the fourth period (May 20–26). The monthly anomalies correspond well with the mean 700-mb. height (fig. 1) and thickness (fig. 5) anomalies. Temperatures were above normal in the Northwest and Southeast and subnormal over the Southwest with an extension northeastward to the Great Lakes.

4. THE CIRCULATION ASSOCIATED WITH ONE OF THE WORST TORNADO WEEKS ON RECORD, MAY 20–26, 1957

In considering the month as a whole the extreme nature of the weather of this week was often referred to. Temperature anomalies were the largest for the month, critical flooding was widespread, and a record number of tornadoes was reported. We have also seen that the general circulation of May was conducive to severe weather anomalies in the Great Plains. In other words the weather regimes of shorter duration, about a week, were superimposed on, or "couched" in, a long-period or monthly flow pattern favorable for tornadoes. It will be further shown that during May 20–26 the daily perturbations were also "couched" in 5-day mean or long waves which encouraged severe storm activity.

Many areas in the Great Plains and Mississippi Valley were afflicted by tornadoes this week (fig. 8D). Destructive tornadoes were particularly prevalent in Oklahoma and northern Texas. Exceptionally bad days were May 20 and 24 when over 30 storms were reported. It is not surprising that a great many tornadoes occurred, because the atmospheric circulation was very favorable for severe local storms.

Beebe [1] published composite charts for conditions which accompanied severe local storms in selected areas of the Mid-West. The distribution of reported tornadoes for this week falls mainly in Beebe's area II. His composite charts for this area (fig. 3 in [1]) bear a striking resemblance to the 5-day mean charts centered on this period (fig. 8). At sea level a sharp trough over the Great Plains was flanked by pronounced ridges along each coast (fig. 8A). The importance of the eastern ridge for severe weather has long been recognized since it is the mechanism that advects moist tropical air over the continent. Apparently the presence of the western ridge serves two major purposes: (1) by flux of vorticity it helps to maintain the trough and ridge downstream, and (2) it deploys the cold maritime Pacific airmasses into the Southwest. In general, then, the surface flow pattern possessed a configuration which brought maritime Pacific and maritime tropical airmasses into juxtaposition over the Plains.

The 700-mb. chart (fig. 8B), which was similar to the sea level map, had a wave of large amplitude with a deep trough over the northern Plains and southern Rocky Mountains, which favored intensification of the daily perturbations as they moved through western United States. The contour pattern was remarkably similar to the corresponding composite (fig. 3 in [1]) and the absolute heights were approximately the same. The mean isotherms also had the same configuration as those of the composite map, and the no-change line (line of apparent zero advection) was located in the southwesterly flow well east of the 700-mb. trough line and quite close to the area of dense tornado reports (fig. 8D).

The indicated cold advection, east of the 700-mb. trough and over the low-level southerly flow, tended to increase the lapse rate in that area. Early studies emphasized the importance of differential advection in producing vertical instability prior to the incidence of severe local storms, but recent studies [11] suggest that it plays only a minor role, although it still may be significant. This period the flow at the mid-tropospheric level (fig. 8B) suggests both advection from the south of the relatively dry air that normally overlies the tropical air and advection from the west of cool Pacific air. The combination of advection of warm moist air surmounted by advection of cool dry air could produce the convectively unstable stratification of airmasses which commonly precedes severe local storms.

At 200 mb. the contour field (fig. 8C) was similar to that at the lower levels with the trough in the West even more pronounced. The associated wind field was also favorable for tornadoes in the southern Great Plains. The jet maximum in the Southwest was situated with its center over eastern New Mexico, so that there is a high probability that northern Texas, Oklahoma, and Kansas, and to a lesser degree central Texas, Missouri, and Iowa were under a favored area of upper divergence which could "trigger" severe local storms [2].

Summarizing, we see that a combination of mid- and low-tropospheric flow patterns prevailed which could produce the convectively unstable lapse rates that are known to precede severe local storms, and a high-tropospheric wind field existed that could lift these lower-level airmasses and "trigger" the tornadoes.

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PREFRONTAL RAINFALL OVER NORTH CENTRAL TEXAS, MAY 12–13, 1957

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1. INTRODUCTION

During the 24-hour period ending 1230 GMT May 13, 1957 moderate to heavy convective-type rain occurred over a large portion of north central Texas. In consideration of the type of precipitation, amounts were not unusually large, ranging from 1 to 5 inches (fig. 1). However, the most interesting feature was that the rainfall area was well organized and located in an area where the surface isobars were curved anticyclonically (fig. 2) for the most part. Although cyclonic curvature usually connotes convergence and anticyclonic curvature divergence, Fletcher [2] has pointed to the existence of heavy rainfall situations in Texas wherein there is low-level anticyclonic curvature and upper-level cyclonic curvature. Such was the case over north central Texas May 12–13.

In general precipitation is the result of saturated air being lifted and is closely associated with horizontal convergence in the low levels and divergence in the upper levels. In addition to topography, the lifting of air can be accomplished by fronts, thermal instability, and isobaric convergence. This investigation has been limited to a synoptic analysis of features related to these lifting processes to determine why north central Texas was a preferred area for moderate to heavy precipitation from 1230 GMT May 12 to 1230 GMT May 13. The synoptic analysis included the general features of the surface and upper-air patterns, stability factors, moisture considerations, upper-level wind field with vorticity concepts, low-level wind distribution, and a system of trajectories for delineating low-level convergence.

2. SURFACE FEATURES

The pressure pattern over Texas and adjacent areas changed very little during the 24-hour period being investigated. In general, there was a weak, slow-moving low pressure center in the Colorado-Kansas area and a quasi-stationary Low over northern Mexico (fig. 2). A cold front was oriented from north to south through western Texas and remained almost stationary west of a line through Altus, Okla., San Angelo, and Del Rio, Tex., until about 0900 GMT May 13. Then the front accelerated and moved to a line near Fort Worth and Waco by 1500 GMT May 13. Surface isobars in the warm sector suggested a south to southeast flow of air into Texas and exhibited anticyclonic curvature over north central Texas.

Both temperature and moisture were reported above normal at stations in the warm sector. The available surface moisture was very pronounced, with dewpoint values ranging from the upper sixties to the lower seventies. This was considerably higher than the 53° F. dewpoints which are considered the critical moisture index for tornadoes and severe thunderstorms [12].

There was little evidence in the surface data that a well organized instability line existed. There was an absence of marked wind shears and large changes in pressure that are normally associated with instability lines. It was noted, however, that radar reports around 0000 GMT May 13 outlined an area 30 miles wide of broken, moderate to strong echoes extending from Sherman, Tex. over Dallas to 30 miles north-northwest of Waco. Hail was indicated in strong echoes 10 miles east of Dallas and 15 miles east of Sherman. Two short lines of broken echoes were also observed. One was of moderate intensity, 8 miles wide, and extended from 10 miles east of

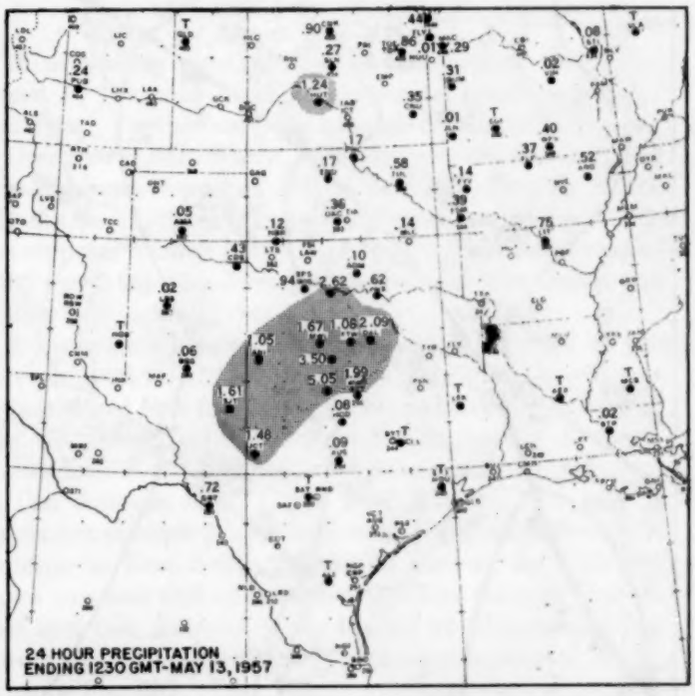

FIGURE 1.—24-hour precipitation amounts for period ending at 1230 GMT May 13, 1957. Area which received one inch or more of rain is shaded.

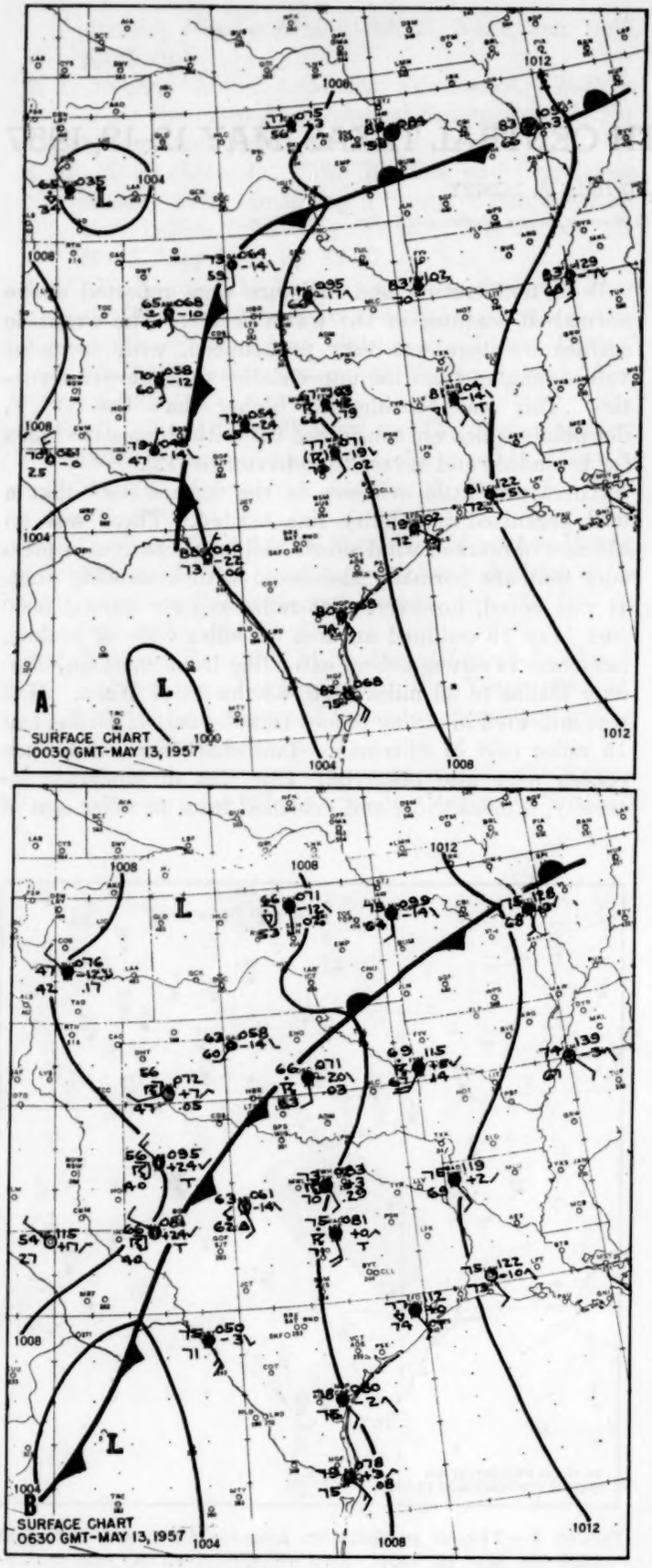

FIGURE 2.—Surface charts for May 13, 1957. (a) 0030 GMT, (b) 0630 GMT. Anticyclonically curved isobars and high dewpoints were dominant over north central Texas.

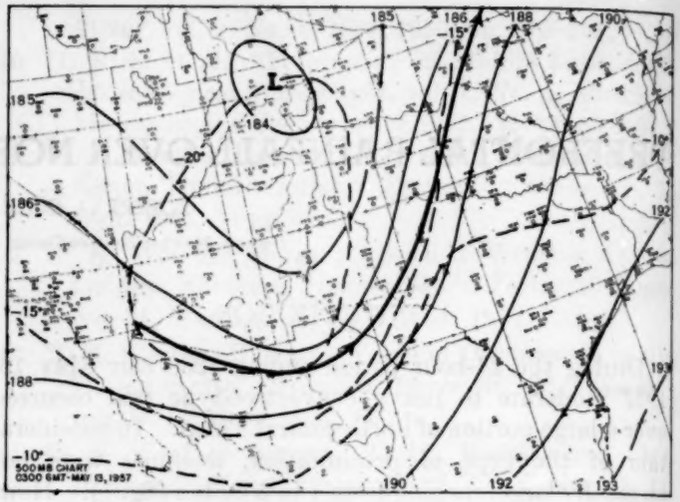

FIGURE 3.—500-mb. chart for 0300 GMT May 13 showing warm air advection (dashed lines) and cyclonically curved contours over north central Texas. Axis of maximum winds is indicated over the Texas Panhandle.

Ardmore, Okla. to 40 miles southeast of Wichita Falls, Tex. The other was strong in intensity, 20 miles wide, and extended from 40 miles south of Mineral Wells, Tex. to 45 miles east-southeast of Junction, Tex. Because the thunderstorm activity was fairly general over the area, hourly continuity of the short squall lines, as well as of the individual cells, was almost impossible. Miscellaneous radar echoes of cells and very short lines were also observed along and ahead of the cold front from Altus to Del Rio.

3. UPPER-LEVEL FEATURES

At the 500-mb. level, a closed Low, located over southeastern Utah at 1500 GMT on the 12th, had moved to central Colorado by 0300 GMT on the 13th with its associated trough extending southward (fig. 3). Cyclonically curved contours prevailed over Texas, a favorable condition for precipitation according to the Olivers [5]. Prior to 1500 GMT May 13, the 500-mb. departure from normal charts showed that heights over extreme western Texas and the Texas Panhandle were 200 ft. below normal, while over north central Texas they were near normal. Cold air advection was indicated in the El Paso-Big Spring area while warm air advection was indicated over north central Texas (fig. 3). A model for pronounced convective instability [5] has been one in which warm air advection is indicated up to the 700-mb. level and then cold air advection up through the 500-mb. level. In this case the 500-mb. thermal pattern did not support the model since there was apparently no cold air injection to trigger the rain-producing mechanism.

The temperature departures from normal were also examined since it was possible the air could have been unusually unstable even though the 500-mb. level lacked cold air advection. On May 12 and 13, when the surface temperatures were above normal ahead of the cold front,

the 500-mb. temperatures were either normal (10-year mean) or a degree above normal. As would be expected, this same pattern was verified by the departures from normal of the 1000–500-mb. layer which showed normal thickness (i. e., mean virtual temperature) ahead of the cold front.

An analysis of the vertical wind structure over Fort Worth at 2100 GMT, prior to a period of heavy rain, indicated mean warm advection from the surface through the 500-mb. level. In detail, however, veering winds indicated warming up to the 850-mb. level, then weak cold air advection was shown as the winds backed slightly to the 700-mb. level, and finally warming again up through the 500-mb. level, as the winds veered with height once more.

This pattern of wind distribution and temperature advection suggested the possibility of an upper cold front forming along a narrow tongue of cold air extending far ahead of the surface cold front; however, a synoptic analysis of the surface and upper-air data did not verify this conclusion satisfactorily. Likewise, radar observations which followed the period of heavy rain at Fort Worth did not disclose the presence of a well organized line of echoes that might be expected along an upper cold frontal surface.

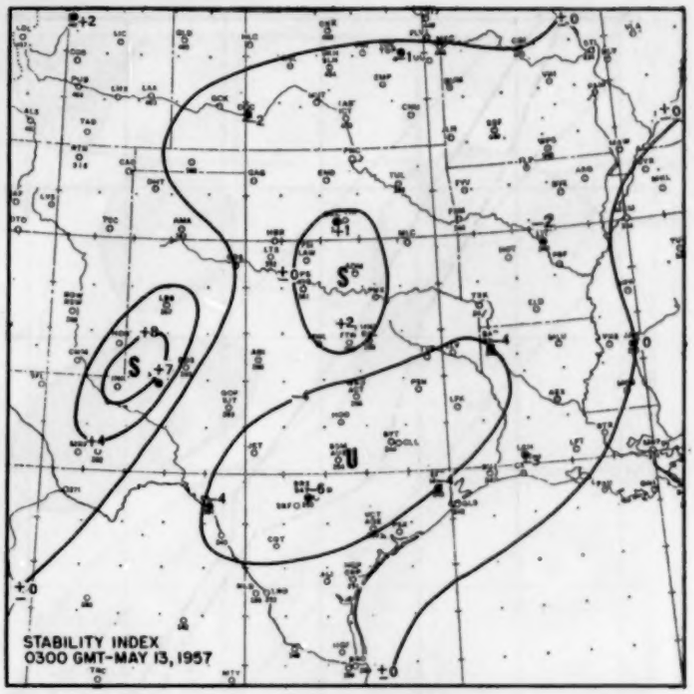

FIGURE 4.—Showalter Stability Index chart for 0300 GMT May 13, which indicated convectively unstable air over Texas ahead of the front.

4. STABILITY FACTORS

In general, the Showalter Stability Index [10] in north central Texas was characterized by large fluctuations from 1230 GMT May 12 to 1230 GMT May 13. The 0300 GMT stability index chart (fig. 4) shows the instability pattern near the midpoint of the 24-hour period. As might be expected, the air appeared to be unstable ahead of the front; however, it was more stable than expected in north central Texas, especially at Fort Worth. Actually the 2100 GMT sounding at Fort Worth (fig. 5a) showed a moist layer up to the 750-mb. level, and correspondingly, a stability index of −4. During the next 6 hours, Fort Worth received over an inch of rain and most of the low-level moisture was apparently lost (fig. 5b). The stability index at this time, 0300 GMT, jumped to +2. Then 6 hours later, moisture had been restored to the 850-mb. level, and the 0900 GMT stability index was computed as −6. This value seemed much more representative of the instability present in the warm sector.

While acknowledging the value of the Showalter Stability Index the Severe Local Storm Center [12] has suggested that the method of computing stability can sometimes be misleading since it is based on the moisture at the 850-mb. level instead of the mean moisture in the low levels. They have found that values of the Showalter Stability Index equal to or greater than +6 indicate convective stability, while smaller positive values may be either convectively stable or unstable. A check of the Fort Worth sounding for 0300 GMT May 13 (fig. 5b) showed that the wet-bulb temperature decreased more rapidly with height than the moist adiabatic rate and thereby indicated the air with the +2 stability index was convectively unstable.

5. MOISTURE CONSIDERATIONS

As previously mentioned, surface dewpoints over Texas ahead of the cold front suggested an ample supply of moisture. Furthermore, the amount of precipitable water in the air over Fort Worth, based on the 2100 GMT sounding (fig. 5a), was computed [13] to be 2.00 inches up to the 750-mb. level. This figure was in general agreement with the reported rainfall in the Fort Worth-Dallas area around 0000 GMT May 13. Fort Worth received 1.08 inches and Dallas 2.09 inches of rain.

A more detailed analysis of the moisture field at the 850-mb. level for 1500 GMT on the 12th (fig. 6a) showed an area enclosed by a line through Corpus Christi, Big Spring, Abilene, Fort Worth, and Fort Smith, having dewpoint depressions of 4° C. or less, with values ranging from zero at San Antonio to 3° C. at Fort Worth. The axis of maximum saturation appeared to be along a line from San Antonio to Fort Smith. By 0300 GMT on the 13th the moist axis had shifted eastward to a line through Shreveport and San Antonio, while the air at Abilene and Big Spring was quite dry with dewpoint depressions of 15° C. or more (fig. 6b). Fort Worth was somewhat drier than it was 6 hours earlier, having a depression of 9° C.

At the 700-mb. level the moisture field (dewpoint depressions of 6° C. or less) was characterized by a moist tongue about 180 miles wide from Del Rio to Altus (fig. 6c)

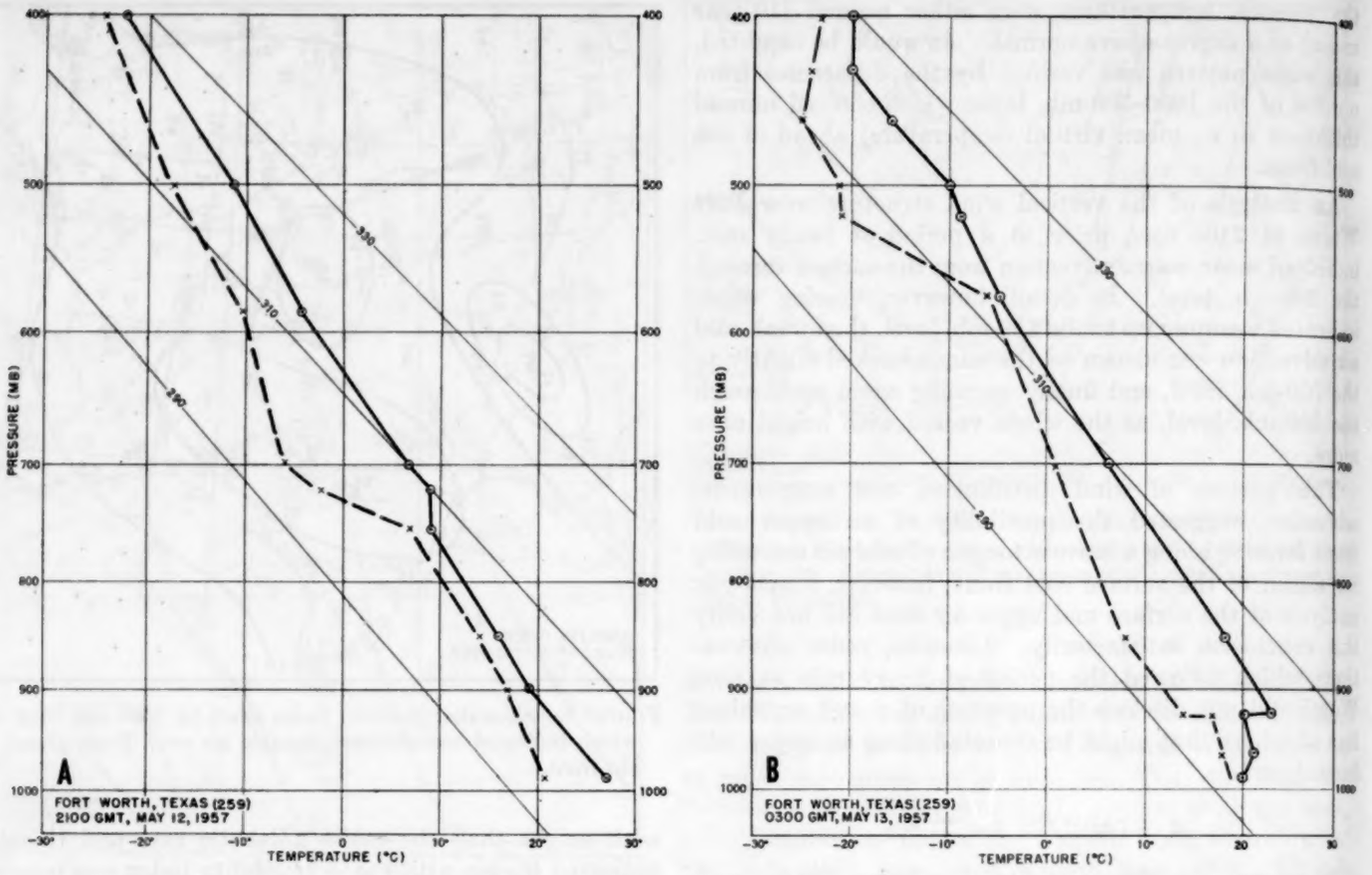

FIGURE 5.—Upper air soundings for Fort Worth, Tex. (a) 2100 GMT May 12, and (b) 0300 GMT May 13. Soundings showed availability and depletion of moisture before and after a heavy rain. Stability indexes were −4 and +2 respectively.

and a dry tongue of about the same width from Corpus Christi to Fort Smith. Fort Worth had a dewpoint depression of 11° C. Twelve hours later this moist tongue (fig. 6d) had shifted eastward to a line near San Antonio and Fort Worth.

On the 500-mb. chart there was much less moisture indicated than at the other standard levels. At 1500 GMT May 12 the air east of a line through Amarillo and Big Spring was dry with dewpoint depressions less than 15° C. A new surge of moisture with dewpoint depressions of 8° C. or less prevailed over Arizona. By 0300 GMT on the 13th, this area of moisture had spread into New Mexico and Kansas while a dry area prevailed south of a line through El Paso, Big Spring, and Lake Charles. Fort Worth at this time had a dewpoint depression of 11° C. During the next 12 hours, the moisture area moved into Oklahoma and Kansas with a narrow tongue dipping southward over north central Texas.

The model for severe storms [12] has provided a combination of conditions favorable for the development of intense convective activity. These conditions have included the requirement of low-level moisture, a middle layer of dry air, and some moisture at the upper levels. It has been suggested that if there is sufficient moisture in the upper levels to support a triggering mechanism for thunderstorms, it would tend to establish a chain reaction. The middle layer of dry air would be cooled to its wet-bulb temperature by the falling precipitation. The increased density of the air would then be used to support downcurrents, which in turn would add to the convective up-currents. In this case, the moisture requirements of the severe storm model were apparently fulfilled.

6. UPPER WIND FIELD AND VORTICITY

In the upper wind field, the 500-mb. jet axis was curved cyclonically along a line near El Paso, Big Spring, and Amarillo, at both 1500 GMT May 12 and 0300 GMT May 13 (fig. 7). The 200-mb. jet axis was similarly located. Riehl and others [8] have related the jet stream to precipitation and have found that an area ahead of the upper trough and to the left of the current is a preferred spot. In this case, it appeared that the jet stream model bore little relation to the situation being examined, especially since the rain seemed to be of a convective type.

The upper wind field was also inspected with respect to the vorticity field and its relation to precipitation. In the examination of this relationship, Petterssen's rule [6] of positive vorticity advection and its effect on surface pressures and vertical motion was used as a model. Petterssen has said that cloudiness and precipitation

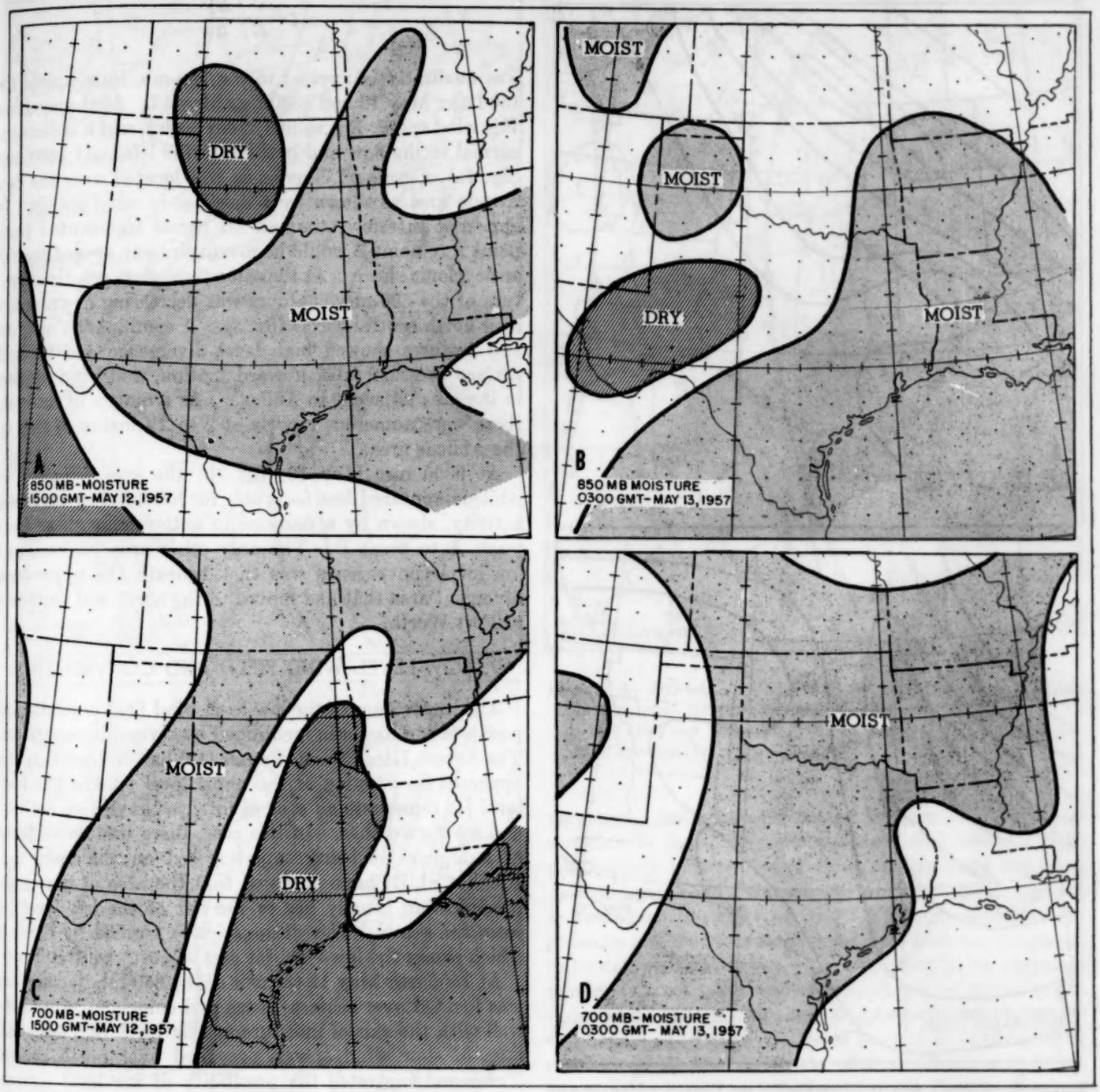

FIGURE 6.—The distribution of moisture is indicated for the 850- and 700-mb. levels. Dry areas were those having a dewpoint depression of 15° C. or greater. (a) 1500 GMT May 12, 850-mb. pattern. Moist area indicated by dewpoint depression of 4° C. or less. (b) 0300 GMT May 13, 850-mb. pattern. (c) 1500 GMT May 12, 700-mb. pattern. Moist area indicated by dewpoint depression of 6° C. or less. (d) 0300 GMT May 13, 700-mb. pattern.

should exist in an area where the relative vorticity decreases downstream, and has implied that it is the advection of vorticity that is important. Riehl et al. [7] have suggested that a vorticity gradient of at least 5×10^{-5} sec^{-1} over 10° of latitude is needed for the rule to work successfully. In this case, the vorticity charts used at NAWAC showed almost no vorticity gradient at the 500-mb. level over Texas until about 1500 GMT May 13, when the 500-mb. trough increased in amplitude and began moving eastward. It was evident then that the vorticity advection had been increased over most of Texas.

Although the geostrophic vorticity gradient over north central Texas was quite weak, a certain amount of low-level convergence and vertical motion was implied from

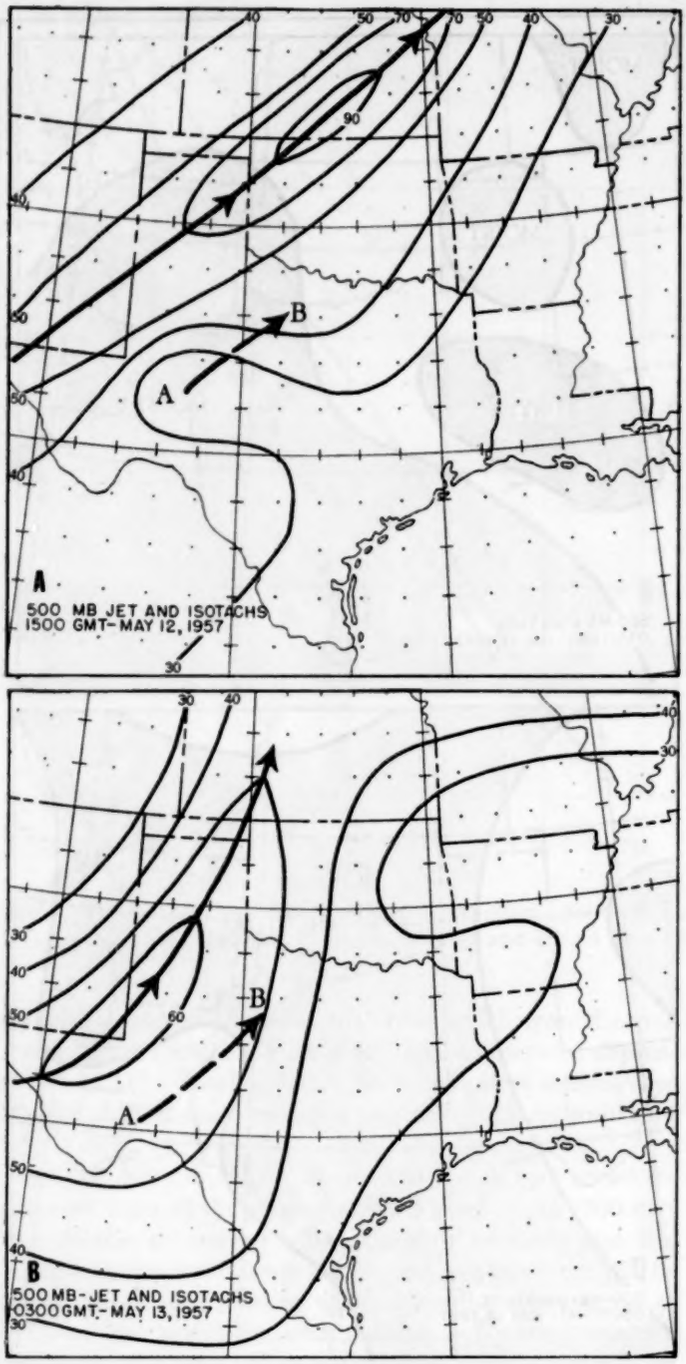

FIGURE 7.—500-mb. jets and isotachs for (a) 1500 GMT May 12 and (b) 0300 GMT May 13. At 1500 GMT north central Texas appeared to be in a favorable position for some cyclogenetic activity, as air moving from A to B would experience increasing anticyclonic shear and decreasing cyclonic curvature. At 0300 GMT the area was less favorable.

the actual winds of the 500-mb. isotach field (fig. 7). Riehl et al. [7], using Scherhag's and Sutcliffe's models which relate upper level vorticity to surface pressure changes, states that surface pressure falls occur where the advection of vorticity decreases downstream at the upper levels. The equation of relative vorticity

$$\zeta=\frac{V}{R}-\frac{\Delta V}{\Delta n}$$

was qualitatively applied to the 500-mb. isotach field for 1500 GMT May 12 and 0300 GMT May 13. In the equation V is wind speed, R is radius of curvature, and n is distance normal to the flow and positive to the left. At 1500 GMT (fig. 7a), a zone of divergence was located over the San Angelo area as shown by a decrease in wind speeds. It appeared therefore, that an air parcel transported from point A to point B would be moving into an area of greater anticyclonic shear. At the same time, the cyclonic curvature of the 500-mb. contours was decreasing downstream over north central Texas (fig. 3). A combination of these two features showed high level divergence and favored surface pressure falls, upward motion, and precipitation in the area adjacent to Abilene. As a matter of interest, there were numerous reports of 2 to 2½ inches of rain in the Abilene area.

At 0300 GMT May 13 (fig. 7b) the area adjacent to Abilene appeared less favorable for low-level cyclogenetic activity, shown by a decrease in anticyclonic shear from point A to point B. The only other area indicative of low-level convergence was that beneath the upper-level divergent area that had moved to the north and northeast of Fort Worth.

7. LOW-LEVEL WIND FIELD AND CONVERGENCE

The importance of the low-level wind field in relation to precipitation has been mentioned by several investigators. The Severe Local Storm Center [12] has noticed that the apparent intersection of the upper-level jet and the low-level jet represents an area of intense convective activity and severe weather. In this case, there was no evidence of a higher jet being superimposed on the lower jet. Riehl et al. [7] have observed that the area of maximum precipitation usually lies to the left of the low-level jet from the south. This observation is verified by figure 8 which shows the low-level jet east of north central Texas.

At 1500 GMT May 12 the axis of the 850-mb. jet (fig. 8a) was located over eastern Texas and coincided reasonably well with the axis of moisture at this level (fig. 6a). An area of slow wind speeds prevailed over north central Texas and suggested the possibility of low-level convergence in the Fort Worth region. By 0300 GMT, the jet axis had shifted westward (fig. 8b) as the 850-mb. frontal trough sharpened and the wind field over Texas was better organized. With the exception of the frontal trough, there was little evidence of convergence over Texas at this time. On the 850-mb. chart for 1500 GMT May 13 (fig. 8c) the organization of the front and wind field appeared to fit the classical model with a wide zone of convergence indicated ahead of the front.

Fulks [4] states that mere instability is not the only requirement for thunderstorm activity and suggests that a triggering mechanism may be found in low-level con-

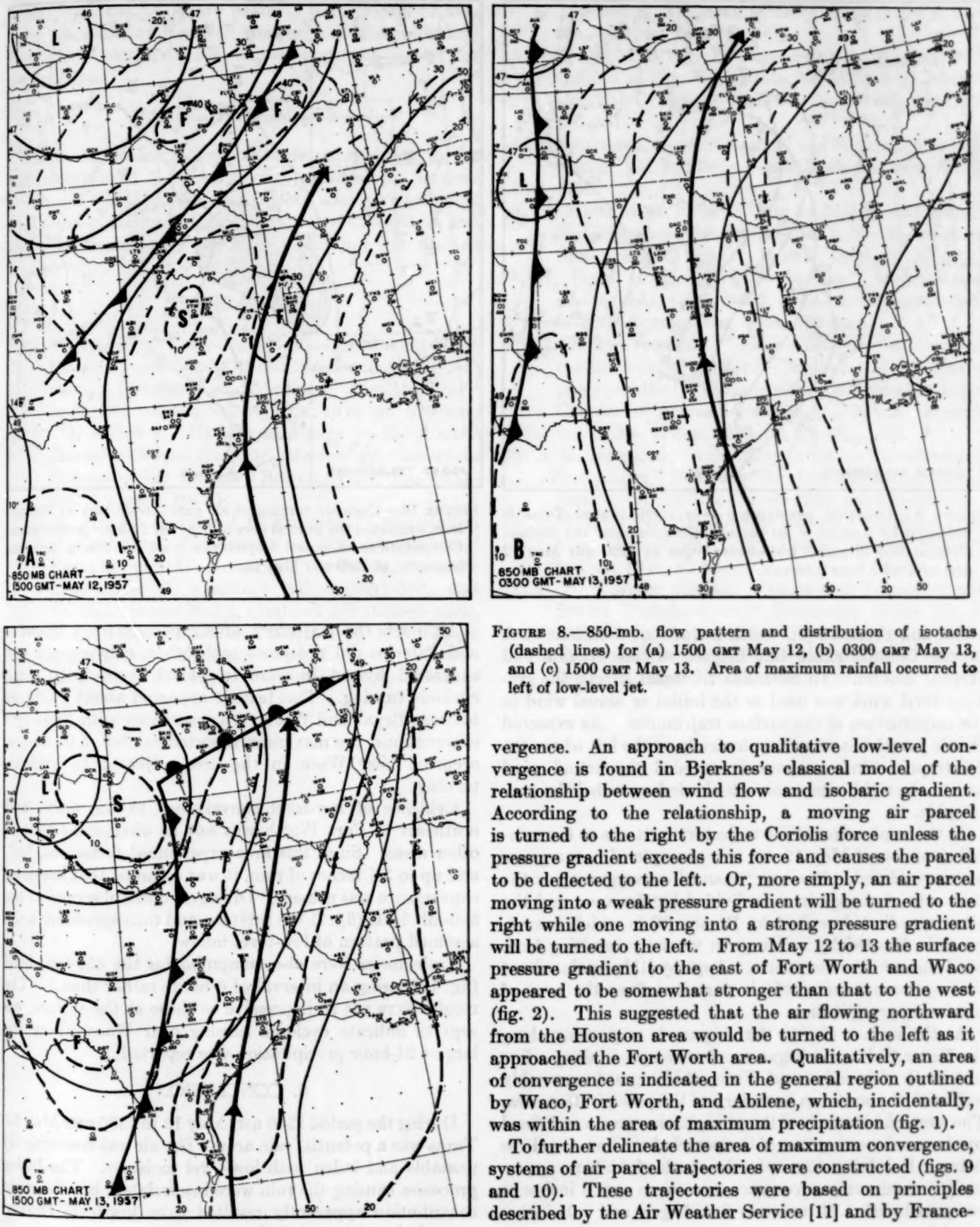

FIGURE 8.—850-mb. flow pattern and distribution of isotachs (dashed lines) for (a) 1500 GMT May 12, (b) 0300 GMT May 13, and (c) 1500 GMT May 13. Area of maximum rainfall occurred to left of low-level jet.

vergence. An approach to qualitative low-level convergence is found in Bjerknes's classical model of the relationship between wind flow and isobaric gradient. According to the relationship, a moving air parcel is turned to the right by the Coriolis force unless the pressure gradient exceeds this force and causes the parcel to be deflected to the left. Or, more simply, an air parcel moving into a weak pressure gradient will be turned to the right while one moving into a strong pressure gradient will be turned to the left. From May 12 to 13 the surface pressure gradient to the east of Fort Worth and Waco appeared to be somewhat stronger than that to the west (fig. 2). This suggested that the air flowing northward from the Houston area would be turned to the left as it approached the Fort Worth area. Qualitatively, an area of convergence is indicated in the general region outlined by Waco, Fort Worth, and Abilene, which, incidentally, was within the area of maximum precipitation (fig. 1).

To further delineate the area of maximum convergence, systems of air parcel trajectories were constructed (figs. 9 and 10). These trajectories were based on principles described by the Air Weather Service [11] and by France-

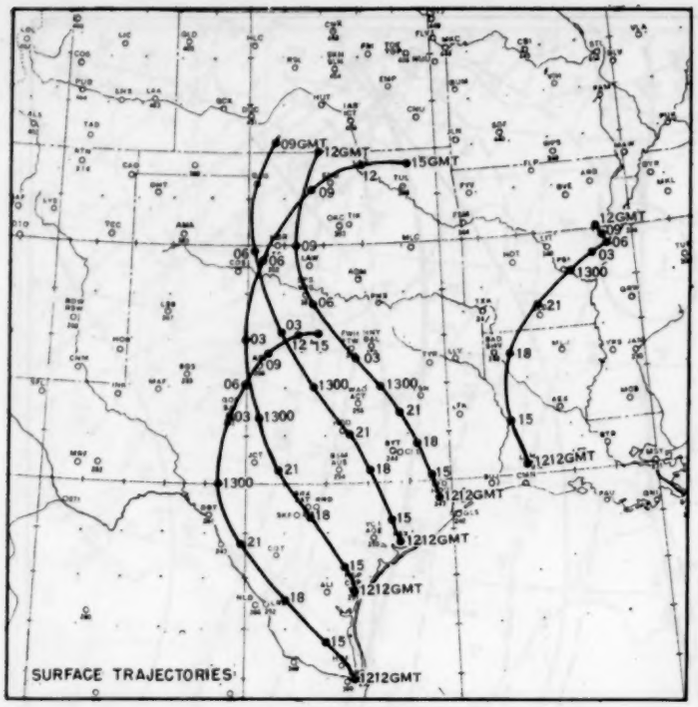

FIGURE 9.—Low-level convergence over north central Texas is indicated by a series of air parcel trajectories near the surface. Computation of parcel trajectories began at 1230 GMT May 12 and covered 3-hour intervals.

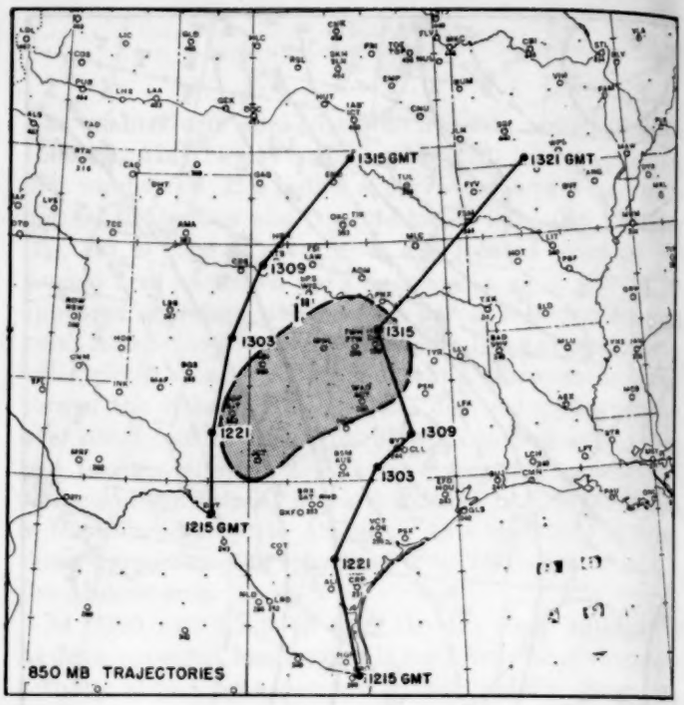

FIGURE 10.—Cyclonic turning of air parcel trajectory at 850-mb. level suggested the general area of heaviest 24-hour precipitation. Computations of parcel trajectories were for 6-hour intervals beginning at 1500 GMT May 12.

schini and Freeman [3], which include accelerations such as the Coriolis effect but neglect surface friction and vertical motion. To minimize frictional effects, the gradient-level wind was used as the initial or actual wind in the construction of the surface trajectories. As expected the air parcel was turned cyclonically to the left where the geostrophic wind component exceeded the actual wind and to the right where the actual wind exceeded the geostrophic.

In the application of the trajectory patterns to the rainfall situation of May 12–13, two concepts of convergence were considered. One was "channel convergence" or the time rate of change in area divided by the area; and the other was that described by Rossby [9] in which convergence is denoted by a change in vorticity resulting from wind shear and/or curvature. Appleby [1] has pointed out that cyclonic turning of air parcels defines the area of maximum precipitation.

At the surface (fig. 9) the air parcels originating along the Texas Gulf coast began areal convergence along a line just south of Junction and Waco, which agreed reasonably well with the southern boundary of the precipitation area. The western boundary of the precipitation area was defined by the areal convergence of the parcels from San Angelo to Altus. Rainfall amounts to the south of Abilene, apparently a maximum convergence area, were over 2 inches as compared with 1.61 inches at San Angelo and 1.05 inches at Abilene.

Although the trajectory of air parcels from Houston and Palacios did not cross each other, convergence was suggested by an increase in parcel speed with some cyclonic turning. This feature appeared about 2100 GMT between Bryan and Waco. In accordance with Appleby's observations, the maximum reported rainfall, 5.05 inches, occurred near Waco in the area adjacent to cyclonic turning.

Evidence of low-level convergence to the north and northeast of Fort Worth was not as obvious as that in other areas. Since this area experienced tornadoes, hail, and up to 3½ inches of rain, it was assumed that low-level convergence was present. Divergence was observed at the 500-mb. level (fig. 7b) in this area and thus agreed with the assumed pattern of low-level inflow.

Trajectories were also computed for the 850-mb. level (fig. 10), using an interval of 6 hours rather than 3. The results were not as impressive as those at the surface, except to indicate cyclonic turning near Waco where the largest 24-hour precipitation was reported.

8. CONCLUSION

During the period 1230 GMT May 12 to 1230 GMT May 13, Texas was a potential rain area. The air was convectively unstable and laden with low-level moisture. The lifting processes causing the rain were interrelated, but the main contribution apparently resulted from low-level convergence induced by wind shears and changes in curvature.

In this case, the trajectory patterns were helpful in outlining the areas of low-level convergence and indicating that north central Texas was a preferred region for precipitation.

ACKNOWLEDGMENTS

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